Development of Bioacoustic Tools for Long-Term, Non-invasive Monitoring of Threatened and Endangered Birds

SI-1392

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Acronyms

CART   Characterization and Regression Tree

DAT   Digital Audio Tape

HNR   Harmonic-to-Noise Ratio

ISHMAEL   Integrated System for Holistic Multi-channel Acoustic Exploration and Localization

kHz   Kilohertz

PAC   Protected Activity Center

SNR   Signal-to-Noise Ratio

SON   Statement of Need

SPL   Sound Pressure Level

Acknowledgements

1. Executive Summary

1.1 Objective

The project's objective was to develop quantitative bioacoustic techniques that can be used to monitor population densities and trends as well as assess the effects of military training and other anthropogenic activities on the population dynamics of threatened and endangered birds, and specifically the Mexican spotted owl.

1.2 Background

Birds that live within visually obscured environments, such as aquatic, arboreal, and nocturnal species, are dependent upon acoustic communication to find mates, care for young, hold territories, and defend themselves from predators. Such species are inherently hard to observe visually and thus monitor, but may readily be studied acoustically. While broadcast acoustic surveys have been conducted for many years to obtain estimates of bird density, long-term population trends and life-history parameters have not been collected because individual identities of calling birds were not known. However, for some species, individual recognition by voice is feasible. In these cases, individual vocal recognition could be an efficient and non-invasive tool for tracking population trends, analogous to photographic identification of large mammals. Quantitative bioacoustic techniques can be used to determine whether individuals' vocalizations can be used to obtain individual signature information. These 'acoustic fingerprints' have already been found in several avian and mammalian species and evidence has been documented for an acoustic basis of kin recognition in some species. Acoustic fingerprints have not been applied as a long-term censusing tool in birds as yet, but recent advances in computing hardware and signal processing have made the approach feasible. The technique was applied here to a species well suited for long-term acoustic monitoring, the Mexican spotted owl (*Strix occidentalis lucida*), one of the DoD's priority species.

1.3 Summary of Result and Accomplishments

Vocal recordings collected as part of an ongoing study of the Mexican spotted owl headed by Dr. Ann Bowles, Co-PI, were used to demonstrate the effectiveness of acoustic techniques as an alternative non-invasive, efficient method for tracking owl movements, measuring population densities, and conducting long-term monitoring of individuals to obtain population parameters. Recordings were collected opportunistically from territorial pairs during the course of a six year study. Vocalizations were digitized and vocalizations were extracted from 121 hours of digital recordings. A total of 961 vocalizations were automatically detected using ISHMAEL and Praat 4.5 acoustic software. Detection rates ranged from 5-96% for different call types. Vocalizations were analyzed in Pratt 4.5 for 14 different acoustic variables. Neural net analysis (NeuralTools 1.0) was conducted on these measurements for classification by sex, and age and individual. The dataset of calls was broken into training and testing (validation) sets for the neural net analysis. Average percent correct prediction for training sets ranged from 99.41 to 100%. Average percent correct prediction for testing sets ranged from 71.4 to 99.2%. Algorithms were developed with the same acoustic measurements using classification and

regression tree analysis (CART) in S-Plus for classifying owl vocalizations by age and sex. Sample sizes from these opportunistic recordings were too low to design algorithms for specific individuals using CART, although the results from the neural net analysis indicate that with larger sample sizes this step will eventually be possible. For age and sex, percent correct classification for the training set was 97.02%. Percent correct classification for the testing set was 89.58%.

1.4 Conclusions

The specific aims and tasks outlined in this project were successfully completed. These data indicate that call detection and discrimination are excellent on multiple levels in Mexican spotted owls. The major call types (territorial four-note hoots, series calls, contact calls, whistles) are easily separable from each other using automated techniques and can also be used to identify sex and age of the owls. The data also support the objective that individual adult males can be discriminated using all calls, particularly four-note hoots and series calls. Adult females can be discriminated using all calls, including contact calls when these calls are produced with sufficient signal-to-noise ratio. Owlets can also be differentiated by whistle calls. Sample size is a key but achievable goal for further development of this technology. Optimal sample sizes would be on the order of 50 or more calls per individual, preferably collected at close range.

Therefore, deployment of a series of remote bioacoustic monitoring acoustic stations will provide a cost-effective and non-invasive system that will allow researchers to track individual owls throughout and across breeding seasons. Acoustic data will allow (1) estimation of population distribution and abundance, and (2) yearly activity in known activity centers, (2) detection of individual adult males and females in known activity centers, and (3) identification of the presence and possibly the sex of owlets.

1.5 Future Directions

Future directions include (1) conducting systematic acoustic recordings to substantially increase sample size of individuals to enhance further algorithm development, (2) expansion and refinement of algorithm development for individual owls, (3) collecting data on sexes of fledgling owlets to confirm the presence of sex differences in the vocalizations, (4) correction for topographical distortion by pursuing methods described in this report (neural net, CART). The work would include innovative approaches borrowed from the study of pattern recognition of visual signals, and development of a stand-alone remote automated system for owl vocalization collection, processing/detection, encoding, and classification. It would also include modeling of acoustic propagation in owl activity centers to determine the effective area covered by automated recording systems.

2. Objective

2.1 Approach

Birds that live within visually obscured environments, such as aquatic, arboreal, and nocturnal species, are dependent upon acoustic communication to find mates, care for young, hold territories, and defend themselves from predators. Such species are inherently hard to observe visually and thus monitor, but may readily be studied acoustically. While acoustic broadcast surveys have been conducted for many years to obtain estimates of bird density (Baptista and Gaunt, 1997), long-term population trends and life-history parameters have not been collected because individual identities of calling birds were not known. However, for some species, individual recognition by voice is feasible. In these cases, individual vocal recognition could be an efficient and non-invasive tool for tracking population trends, analogous to photographic identification of large mammals.

Quantitative bioacoustic techniques can be used to determine whether individuals' vocalizations can be used to obtain individual signature information. These 'acoustic fingerprints' have already been found in both avian and mammalian species (Baptista et al., 1997; Bauer and Nagl, 1992; Chapman and Weary 1990; McCowan and Reiss, 2001; McCowan and Hooper, 2002; Rendall et al., 1996; Robisson et al., 1993; Tooze et al., 1990), and evidence has been documented for an acoustic basis of kin recognition in some species (Gouzoules and Gouzoules, 1990; Rendall et al., 1996). Acoustic fingerprints have not been applied as a long-term censusing tool in birds as yet, but recent advances in computing hardware and signal processing have made the approach feasible. The technique was applied to a species well suited for long-term acoustic monitoring, the Mexican spotted owl (*Strix occidentalis lucida*).

2.2 Selection of Study Species

The Mexican spotted owl, a nocturnal terrestrial bird inhabiting the Western United States and Mexico, was listed as threatened by the U.S. Fish and Wildlife Service (USFWS) on April 15, 1993. The Recovery Plan for the Mexican spotted owl (USFWS 1995) has established three criteria for its delisting: (1) the populations of targeted areas must be stable or increasing after 10 years of monitoring, (2) habitat quantity and quality must be scientifically assessed to determine whether it can support viable populations of Mexican spotted owls, and (3) a long-term management plan must be designed to ensure appropriate management for the owl and its habitat.

Current USFWS-sanctioned survey procedures require four complete calling surveys per season that cover all the suitable habitat in a targeted area at half-mile intervals (Forsman, 1983; U.S. Forest Service 1994, 1996). However, these surveys only measure occupancy and fledging success. Long-term banding studies are needed to obtain other important population parameters, such as survival to the age of first reproduction and interval between successive nestings. A recent analysis of data for the northern spotted owl (*S. o. caurina*) suggests that such population parameters provide the most sensitive measure of population trends (Taylor and Gerrodette,

1993). However, capture for banding poses risks to subject birds and cannot be conducted over large areas practically.

The Mexican spotted owl is an ideal species for a first attempt to census birds using acoustic fingerprints. It is nocturnal; its favored habitat is dense forest; and it avoids predation by means of cryptic coloration and behavior, making visual communication prohibitively difficult. It is unsurprising, therefore, that the spotted owl has a relatively large repertoire of calls and that mated pairs use vocalizations to defend territories and coordinate breeding activities (Forsman et al., 1984; Ganey, 1990). The territorial four-note hoot can be detected reliably at 400 m, and at up to 3 km under ideal conditions. Sexes can be distinguished by voice, with males producing calls having substantially lower pitch than those of females. Sexes also differ in the composition of their repertoire. Sex differences simplify the task of recognizing individuals by cutting the number of possible matches in half.

The species exhibits high mate and territory fidelity (Gutierrez et al., 1995), making it possible to find and record the same individuals within breeding seasons and from year to year. It is a threatened species found on military lands or under military airspace. Critical habitat for the species has now been identified in Arizona, New Mexico, Colorado, and Utah (USFWS 2001). Mexican spotted owls are typically associated with steep, northeast-facing slopes in dense, multistoried old-growth forest that is often sparsely inhabited and therefore suitable for military training activities, including low-altitude, terrain-following military training flights. Concerns about noise exposure and mid-air collisions with Mexican spotted owls have already led to one consultation with the potential to restrict critical U.S. Air Force activities (USFWS 1997) in this region. Therefore, automated methods for locating and identifying individual owls would represent a more cost-effective method for fulfilling long-term monitoring requirements. Also, favored habitat is difficult to access in areas with poor road coverage, increasing the chances that owls will be undercounted. For example, surveys conducted in the Gila National Forest in the late 1980s (Fletcher and Hollis 1994) failed to find large areas that proved to be occupied during the more extensive 2000 – 2005 surveys conducted by ACC (Bowles pers. comm.)

Automation is entirely feasible for identifying this species. Not only do Mexican spotted owls exhibit high mate and site fidelity, but they also are highly vocal during predictable seasons and times of day. Mexican spotted owls call mainly from March-November and are relatively silent from December-February (Ganey, 1990). Calling activity increases from March through May, although females are largely silent while on the nest in April and early May, and then declines from June through November (Ganey, 1990). On a daily basis, calling activity is greatest during the 2-hour period following sunset, with smaller peaks 4-8 hours after sunset and just before sunrise. Mexican spotted owls have a wide repertoire of calls (Forsman et al., 1984, Ganey, 1990) that are relatively low-pitched and composed of pure tones (Fitton, 1991). The most common vocalization, used more often by males, is a series of four unevenly spaced hoots. Females frequently use a clear whistle ending with an upward inflection as well as a series of sharp barks. Forsman et al. (1984) described 14 calls for the northern spotted owl, of which 10 were also reported by Ganey (1990) for Arizona birds.

2.3 Specific Aims

The specific aims of this research include:

1. Determining whether Mexican spotted owls exhibit systematic variation in the acoustic structure of their calls sufficient to distinguish enough individuals for an exhaustive inventory of owls in a local cluster of territories.
2. Examining whether the acoustic structure of calls will be sufficiently invariant over time to allow individuals to be recognized between as well as within breeding seasons.

Mexican spotted owl vocalizations were obtained from a study conducted for ACC/CEVP in the Gila National Forest to meet the requirements of a USFWS Biological Opinion. Data were collected by Dr. Ann Bowles during the study as a source of potential information on territorial fidelity of unbanded birds. As a part of this study, sound monitoring data collected using an acoustic array. These data were examined to assess whether owls are sufficiently vocal within preferred activity centers to permit adequate samples of calls to be obtained by automated listening stations (See Appendix).

The research in this SEED project was under the Statement of Need (SON) entitled "Development of innovative inventory and monitoring techniques for high priority threatened and endangered species)". The objective of this SON was to develop new and innovative techniques for conducting inventory and monitoring of high priority, terrestrial threatened and endangered species on Department of Defense lands. This SEED project was intended to demonstrate a proof-of-principle. If additional follow-up studies continue to be successful, a computer-based bioacoustic assessment system for use by appropriate management agencies to measure owl densities, distribution and demographics in relationship to military and other anthropogenic activities will be designed and developed.

2.4 Tasks

The specific tasks to be accomplished during this research period included:

1. Digitization of Mexican spotted owl recordings.
2. Quantitative and statistical analysis of owl vocalizations.
3. Development of pattern recognition program for acoustic signature analysis.
4. Production of a Final Report to SERDP.

In addition to these tasks, the data collected by Dr. Ann Bowles during the study conducted for ACC/CEVP in the Gila National were examined to assess whether owls are sufficiently vocal within preferred activity centers to permit adequate samples of calls to be obtained by automated listening stations (See Appendix).

2.5 Benefit

        The research in this project will lead to the development of an innovative set of bioacoustic assessment tools as an alternative cost-effective and non-invasive method for monitoring population densities and trends in species for which vocalizations play a primary role in social communication and territory maintenance. This research also has important and broader implications for studying the effects of military habitat alteration on threatened and endangered wildlife because the techniques could also be used to assess the effects of noise from military activities on wildlife distribution and behavior. The tools developed from this work will allow future investigations to address important conservation questions pertaining to military training activities better and more efficiently.

3. Background

3.1 Status of the Mexican spotted owl

Historical alteration of habitat due to timber management practices, with a threat of these practices continuing, and the danger of catastrophic wildfire were the primary reasons for listing the Mexican spotted owl as a threatened species in April of 1993 (USFWS, 1995). Once listed, the Fish & Wildlife Service was required to designate critical habitat for the Mexican spotted owl under section 4(a)(3) of the Endangered Species Act. Critical habitat is essential to the conservation of the owls, since it supports populations of owls and/or provides the habitat requirements necessary for roosting, nesting, and foraging (USFWS, 2000). Critical habitat was first designated in June of 1995, removed in March of 1998 due to legal issues, and re-designated with amendments as a final ruling effective March 2001 (USFWS, 2001). In total, 1.9 million hectares of Federal lands were divided into 24 critical habitat units in Arizona, Colorado, New Mexico, and Utah by the Fish & Wildlife Service to help protect the Mexican spotted owl (USFWS, 2001).

The Mexican spotted owl Recovery Plan of 1995 (USFWS, 1995) set up recovery units in both the U.S. and Mexico to identify the owl's range. The recovery plan contains five basic elements to meet the recovery goal of removing the Mexican spotted owl from the threatened species list. The basic elements consist of: (1) a set of delisting criteria; (2) procedures to execute oversight and coordination responsibilities; (3) recommendations for habitat and population monitoring; (4) general strategies that consider owl's needs and habitat use in order for management to provide habitat protection; and (5) a research program to gather information to further understand Mexican spotted owl biology and the effects of anthropogenic activities on the owl and its habitat.

Currently, there are no reliable estimates of population size for the Mexican spotted owl in the US. In 1991, the Fish & Wildlife Service provided an estimate of 2,160 Mexican spotted owls for the entire US. However, in 1999, a pilot study conducted by Ganey et al. (1999) estimated 2,950 owls in just 1 of 6 recovery units found within the US (USFWS, 2001), providing evidence that owl populations have been undercounted due to the logistic challenges of conducting surveys. Clearly, a reliable and less costly method for collecting data on the number of individual owls in an area is needed for management decision-making and conservation of this threatened species.

3.2 Ecology and Biology of the Mexican spotted owl

The American Ornithologists' Union recognizes three subspecies of spotted owl, including the Mexican (*Strix occidentalis lucida*), the Northern (*Strix occidentalis caurina*) and the California (*Strix occidentalis occidentalis*) spotted owls. The Mexican subspecies can be distinguished from the other spotted owls by lighter coloration irregular white and brown spots on its head, back and abdomen (USDIFWS, 1995). It is geographically isolated from the other subspecies. A study comparing the genetics of the three spotted owls has shown the Mexican subspecies to be significantly distinguishable (Barrowclough and Gutierrez, 1990). As a result,

prolonged geographic isolation is likely, along with the possibility that the Mexican spotted owl may indeed represent a distinct species from the California and Northern subspecies.

The Mexican spotted owl has a fragmented distribution throughout its range, which extends north from Aguascalientes, Mexico, through the mountains of Arizona, New Mexico and West Texas to the canyons of Utah, Colorado and the Front Range of central Colorado (USFWS, 1995). Home range sizes vary depending on geographic area, habitat, and prey availability, and can include 261 – 1,487 ha for individuals and 381 – 1,551 ha for pairs (Ganey and Balda, 1989; Ganey et al., 1999; USDIFWS, 2000). Throughout their range, Mexican spotted owls commonly use mixed conifer forests (Johnson and Johnson, 1985) dominated by Douglas-fir and/or white fir, as well as madrean pine-oak forests (USFWS, 1995). For nesting and roosting, the owls commonly use Douglas-fir trees in closed canopy forests, or caves and cliff edges within rocky canyons (USFWS, 1995). In contrast, the owls utilize a wider variety of forest conditions for foraging (USFWS, 2000).

Mexican spotted owl prey types vary throughout their range (USFWS, 2000), and include animals from five mammalian orders, five avian orders, one reptilian suborder and from a variety of insect genera (Ward and Block, 1995). Woodrats (*Neotoma*) are an important component of the diet in areas where prey types have been studied. In general, the spotted owl is nocturnal (Forsman et al., 1984), however, they can be opportunistic diurnal foragers if prey are in close proximity to an owl's roost (Delaney ad Grubb, 1999; Bowles, pers. comm). Spotted owls use sound and sight to locate prey from perches, then pounce and seize the prey with their talons (Forsman, 1976). The owls may also capture flying prey, like bats, birds and insects.

The Mexican spotted owl is highly social, spending only the period when winter conditions force them to migrate to lower elevations (generally November to February) in isolation. Seasonal movement patterns are variable depending on conditions. Some individuals inhabit an area year-round, while others show some shifts in habitat use patterns within the same general area, or migrate considerable distances of 20-50 km during the winter (Ganey and Balda, 1989; Willey, 1993). The owls only breed under good conditions, although they often return to the same stand, or at least the same general area, to roost and defend their territories regardless of reproductive status (Ganey and Block, 2000).

Ganey (1988) documented the reproductive chronology of the Mexican spotted owl in Arizona. Courtship began around March. During courtship, pairs roosted together during the day, and then called to each other at dusk. Females laid eggs in late March/early April, and incubation started shortly afterwards. Incubation time was assumed to be 30 days and was carried out by the female alone. During incubation and for the first half of the brooding period, the male did most or all of the foraging, and the female stayed at the nest, leaving only to defecate, regurgitate pellets or receive prey from the male (Forsman et al., 1984; Ganey, 1988). Strict female attendance at the nest is believed to be crucial to chick survival prior to thermal independence, and less so to protect the nest from potential predators (Delaney and Grubb, 1999).

Following incubation, the eggs hatched in early May, and nestlings fledged four to five weeks later. Actual dispersal began in mid-September through early October (Ganey, 1988). In a study carried out in Utah, adults were found moving from natal areas to surrounding areas within

their home ranges during August and September. They were far from juveniles when dispersal commenced (Willey and van Riper, 2000). Dispersal is initiated abruptly, and juveniles show no apparent directional pattern (Willey and van Riper, 2000). The median dispersal distance shown for juveniles was 16.9 km in mixed conifer forests, and 25.7 km in canyonlands, although few individuals have been observed actually settling and finding mates. During dispersal, the primary causes for juvenile mortality were identified as predation and death caused by exposure, or starvation, disease and dehydration (Willey and van Riper, 2000). Although both adult and juvenile owls are preyed upon, the extent to which this occurs is unknown (USFWS, 1995). Known predators of Mexican spotted owls include Golden eagles, Great-horned owls, Red-tailed hawks, and Northern goshawks (Rinkevich et al., 1995).

Adult Mexican spotted owls have a survival rate of 0.8-0.9 (USFWS, 1995), defined as the probability of an individual owl surviving from one year to the next (USFWS, 1995). Compared with adults, juvenile survival rate was substantially lower (0.06 - 0.29). However, these estimates originated from studies of inadequate duration, or from studies that were not specifically designed to estimate survival rates (USFWS, 1995). In effect, managers would benefit from a method that can positively identify juveniles after they disperse and settle into adulthood, which is when most surveying is conducted. Tracking studies are valuable, but represent a particular risk to juveniles (USFWS, 1995).

3.3 Communication in the Mexican spotted owl

The vocal repertoire of the Northern subspecies was first described by Forsman *et al.* (1984), and consisted of 14 call types. In 1990, Ganey described ten of the 14 call types for the Mexican subspecies in Arizona, including territorial hoots (four-note hoot, series calls), contact calls, and a bark series. They also recognized cooing calls, an alarm call, a nest call, and a juvenile begging call. Ganey found a high degree of structural similarity between the two subspecies with respect to frequency and time characteristics of vocalizations. Fitton (1991) found the calls to be composed of pure tones of relatively low pitch (USFWS, 1995). Both Forsman et al. (1984) and Ganey (1990) discovered differences in pitch between female and male calls, with a higher pitch noted for the female, allowing for easy identification between the sexes (Kuntz, 1998). In addition, males commonly use the four note hoot, while females often use the contact call, a clear whistle ending with an upward inflection, as well as barks (USFWS, 1995).

Calling activity of the Mexican spotted owl is infrequent from November through January, when spotted owls are non-reproductive and often solitary (Ganey, 1990). Calling begins during territory establishment and continues through dispersal, with the greatest vocal activity occurring from March through June during the nesting season (Ganey, 1990) when adult male and female vocal exchanges are needed to maintain the territory, defend the nest and young against predators, and coordinate breeding activities. Females were relatively silent through April and May, during incubation and brooding, when they are mainly restricted to the nest site. Environmental factors, such as weather conditions and phases of the lunar cycle, have been shown to play a significant role in the calling activities of Mexican spotted owls. Call frequency was greater during the last quarter and new moon phases, as well as on calm, clear nights (Ganey, 1990).

Calling patterns were shown to occur throughout the night; however, the owls were most vocal during the two hours after sunset (Ganey, 1990). Actual calling bouts of both males and females were found to last an average of 9.9 minutes (Ganey, 1990). Mated pairs frequently foraged in different locations within their large home ranges, so to locate each other, they often used the primary four note hoot, which is audible over long distances (Ganey, 1990). Long-range communication can be an effective means for mated pairs to communicate, assuming the pairs can recognize each other by their calls. Individual differences in all call types have not been tested, although the presence of individual variation in the male's four-note location call has been reported (Kuntz, 1998). In addition, Kuntz also reported population-level variation suggesting that Mexican spotted owls may exhibit some vocal plasticity in their calls and calling behavior, although the cause of the plasticity (morphological or learned) is unknown. This systematic acoustic variation may be useful for surveying individuals and their movements as well as examining the effects of military and other anthropogenic noise on owl vocal acoustic structure and behavior.

3,4 Signal Design and Transmission

The analysis of vocal communication requires an understanding of how long-distance vocalizations are designed for transmission across environments (reviewed in Owings and Morton, 1998). For effective signal transmission certain distorting properties must be overcome or successfully exploited to maximize signal-to-noise ratios and maintain signal effectiveness. Wiley and Richards (1978, 1982) and Morton (1975) have investigated these distorting properties across a variety of habitats and have identified two categories of problems they create, attenuation and degradation, which must be surmounted to maintain signal efficacy. Attenuation is the process by which signal intensity decreases in force or strength as signals propagate across a habitat. It is caused by topographic shadowing, absorption by substrate and ground cover, and atmospheric absorption, scattering, and boundary interference. Degradation is the destruction of acoustic signal structure and includes both reverberation and amplitude fluctuations. Because attenuation and degradation are important properties of acoustic signal transmission, many species have evolved signals that are spectrally and temporally designed to match the terrain, atmospheric conditions, and naturally-occurring ambient noise (e.g., wind, other species' signals) in a given habitat (Morton, 1975). Animals can also alter their daily patterns and location of calling to minimize disruption of their signals (Bradbury and Vehrencamp, 1998; Wiley and Richards, 1978, 1982).

In addition to habitat structure and their associated atmospheric conditions, other factors contribute to signal design. The motivation-structural rule of bird and mammal vocalizations, for example, describes the link between the functions of vocalizations and their structure. Specifically, aggressive signals of many species tend to be broadband and lower in frequency in comparison to affiliative or fearful signals, which tend to be more tonal and higher in frequency. This rule probably evolved to exploit risk-assessment systems of receivers that used the frequency and bandwidth of sounds to estimate size (Morton, 1977; Owings and Morton, 1998). The frequency and bandwidth of sound are, in turn, linked to body size through the physics of sound as it relates to size of the vocal apparatus. In contrast, the structure of narrowband, high-pitched "seet" hawk-alarm calls of small perching birds appears to have been shaped for

minimum localizability or detectability by the auditory systems of "eavesdroppers", i.e., the hawks that may prey on conspicuous callers (Klump, 1986; Marler, 1959). Many signals have structural design features that function to enhance their efficacy by exploiting characteristics of receiver systems such as attention and motivation (Guilford and Dawkins, 1991; Owings, 1994). The relative importance of the acoustic medium and the receiver systems of others as shapers of signal structure varies in part with the distance over which communication takes place. Over larger distances, properties of the medium become proportionately more important (Owings and Morton, 1998).

Source levels of vocalizations are also important because they affect territory maintenance and female choice (Bradbury and Vehrencamp 1998), although much less research effort has targeted the adaptive properties of vocal amplitude. In the case of the Mexican spotted owls, the preferred calling time occurs when atmospheric conditions promote long-range propagation of territorial calls. Throughout most of the range, the signal-to-noise ratio of their calls is low (Bowles, unpub. data).

Thus specific aspects of signal type acoustic structure are dependent on multiple factors: (1) the atmospheric conditions of the habitat in which signaling occurs (Bradbury and Vehrencamp, 1998; Morton, 1975; Morton, 1977; Wiley and Richards, 1978, 1982); (2) the distance the signal must travel to have its effect; (3) the properties of the assessment systems of targets and eavesdroppers; (4) the anatomy and vocal tract morphology of the vocalizer; and (5) the motivational state of the vocalizer. Spotted owl calls, which function primarily as long-distance signals, exhibit acoustic structures that appear adapted to their function and surrounding natural environment.

3.5 Acoustic Signatures in Vocal Communication

In addition to the effects of environmental conditions and call function on signal structure across call types, a number of past studies have indicated that animal vocalizations contain individual distinctiveness or population differences within specific signal types. Mammalian and avian species as varied as nonhuman primates (Butynski et al., 1992; Chapman and Weary, 1990; Goedeking and Newman, 1987; Hammerschmidt and Todt, 1995; Hauser, 1991; Hauser, 1992; Hohmann and Vogl, 1991; Jones et al., 1993; Macedonia, 1986; Maeda and Masataka, 1987; Bauer and Nagl, 1992; Barrowclough and Gutierrez, 1990), wolves (Tooze et al., 1990), raccoons (Seiber, 1986), bats (Boughman, 1997; Boughman, 1998; Gelfand and McCracken, 1986; Scherrer and Wilkinson, 1993), birds (Bauer and Nagl, 1992; Weary et al., 1990) and penguins (Robisson et al., 1993) show systematic acoustic differences in their calls across individuals or populations. Many species exhibit acoustic distinctiveness in various temporal and frequency parameters that likely provides the acoustic basis for individual or kin recognition (Bauer and Nagl, 1992; Maeda and Masataka, 1987; Robisson et al., 1993; Tooze et al., 1990). In addition, dialects have been well documented in many avian species (Mundinger, 1982; Sorjonen, 1987; Wright, 1996) and some cetaceans (pilot whales: Taruski, 1979, sperm whales: Weilgart and Whitehead, 1997, orcas: Ford, 1991; Ford and Fisher, 1983). For example, orcas exhibit dialectal differences that directly correspond to the stability of the matrilineal social structure found in this species (Deecke et al., 2000; Miller and Bain, 2000). Recent studies suggest that some primate species exhibit population and social group differences in call structure (e.g., chimpanzees: Mitani and Brandt, 1994; Mitani et al., 1992; marmosets: Elowson and Snowdon, 1994) indicating a possible function for social recognition and/or cohesion. Many

of these studies on dialectal differences between populations indicate that a number of species may exhibit plasticity in their vocal behavior that cannot be attributed to genetic differences. All the studies suggest that many animal vocal repertoires exhibit systematic acoustic differences relating to individual, sex, age or population identity. The potential for acoustic variation of this type in spotted owls is clear. If systematic acoustic variation exists in the calls of Mexican spotted owls (Kuntz, 1998) then this variation can be used as a non-invasive method to census populations, track individual migration patterns, and monitor territory use as well as other population patterns in this species (Baptista and Gaunt, 1997; Reby et al., 1998a, 1998b). If bioacoustic methods can be used to detect changes or differences in these patterns, they can be used to monitor different types and levels of human disturbance.

4. Materials and Methods

4.1 Data Collection

Calibrated digital recordings of owls were collected by Dr. Ann Bowles, Co-PI, as part of an ongoing study of the Mexican spotted owl for the Air Force (ACC 2002) from 2000-2005. Data were collected using a Marantz PMD 670 digital audio recorder or Sony digital audio tape (DAT) recorder connected to an ACO 7013 ½-inch microphone. A calibration signal was laid down with a Larson-Davis CAL200 before and after each session. Distances to owls were estimated by field staff during each call bout. Over 627 hours of recordings were collected, of which 121 hours were usable for the present study.

Subject owls occupied known territories under military training route VR-176, which crosses the Gila National Forest, New Mexico. The study area was a 12.5 mi x 15 mi area located in the northern Mogollon Range, centered on Corner and Bearwallow mountains. The area covered a dense cluster of 44 Protected Activity Centers (PACs) formally recognized by the U.S. Forest Service (USFS), centered on Corner and Bearwallow mountains. Most of the habitat in the study area was composed of Douglas-fir, mixed-conifer, white fir, and ponderosa pine forest. During the 2000 – 2005 surveys, owls were found to use nearly twice as much of the area as expected based on PACs developed during the earlier surveys. Both survey effort (Fletcher and Hollis 1994) and changes in habitat (rainfall conditions and a large fire on the western side of Bearwallow Mountain in 1998) are likely to explain the difference. Population increase did not explain the difference, as the counts of pairs were similar during both sets of surveys.

The data were collected as part of an ACC/CEVP-sponsored experimental study of aircraft overflight effects (ACC in prep). The work was mandated by a USFWS Biological Opinion, which tasked the U.S. Air Force and a NATO-sponsored German Air Force Squadron based out of Holloman Air Force Base to determine the effects of military jet aircraft overflights on owl occupancy, reproductive success and behavior.

The recordings included adult, subadult, and fledgling owls. Subjects were chosen opportunistically based on accessibility of the activity center and willingness to call with human observers present. Birds were accessible in recognized in some of the activity centers during multiple years, allowing variation over time to be monitored. However, only two birds (breeding females in two territories) were banded because study goals would have been compromised by the disturbance of capture and banding. Recordings were collected during reproductive monitoring. Owls were recorded when calling spontaneously or after they had been stimulated to call so observers could find them. When possible, recordings were collected within 20 m of calling birds. Range to the owl, identity of the caller, position relative to the microphone, and perch elevation were collected during each recording.

4.2 Data Analysis

The following tasks were accomplished with the vocal recordings: (1) digitization of Mexican spotted owl recordings, (2) quantitative and statistical analysis of owl vocalizations, and (3) development of pattern recognition program for acoustic signature analysis. Vocalizations were digitized at a sampling rate of 44.1 kilohertz (kHz) and analyzed for several acoustic variables. Call recognition software designed to process transient animal vocalizations, the Integrated System for Holistic Multi-channel Acoustic Exploration and Localization (ISHMAEL) was used to automatically detect and extract the vocalizations from digitized recordings, using a matched template design. Praat 4.5 phonetics software was used as an alternative method to detect and extract vocalizations. It tracks the voiced portions of the fundamental frequency of the vocalizations. Several spectral and temporal variables were measured from each extracted vocalization. The variables were then entered into a neural net analysis in NeuralTools 1.0. Classification and Regression Tree analysis (CART) in S-Plus statistical software was used to determine how well vocal acoustic structure could distinguish among sex/age classes and individuals within each sex/age class. Details of the analyses are provided under the "Approach" section for each task in "Results and Accomplishments" below.

5. Results and Accomplishments

5.1 Aim 1 & 2: Determining whether Mexican spotted owls exhibit systematic variation in the acoustic structure of their calls sufficient to distinguish individuals over time. Task 1: Digitization of owl vocalizations

The extraction of vocalizations recorded from owls in 27 territories during 2000-2005 was completed. The 121 hours of opportunistic recordings yielded 961 calls. Vocalizations types included four-note hoots (N = 358), multi-note series calls (N = 152, variable hoots produced in agonistic contexts), contact calls (N = 116), barks (N = 55) and whistles (N = 280) (Figure 1). Note the clear spectral differences between hoots, contact calls and owlet whistles. As expected, four-note hoots and series calls were produced most often by adult males. Adult females produced all the contact calls in this dataset, although males did occasionally produce them as well. Barks were produced by both sexes. Whistles were contact and begging calls produced by owlets. Therefore all sex and age classes and all the common vocalizations produced by spotted owls were represented in the vocal sample.
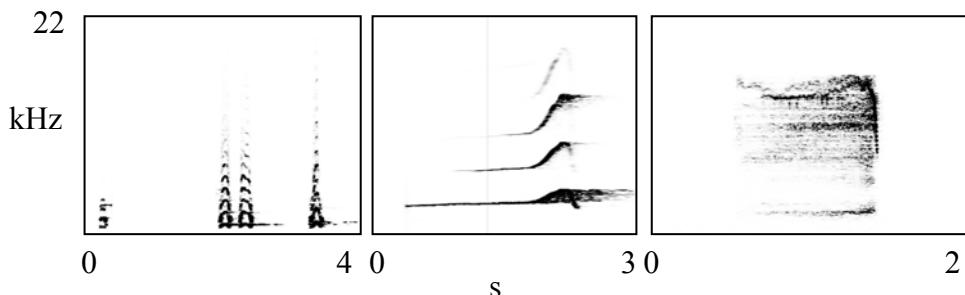
Figure 1. Major vocalization types produced by Mexican spotted owls (from left to right: four-note hoots, contact call, owlet whistle).

5.2 Aim 1 & 2: Determining whether Mexican spotted owls exhibit systematic variation in the acoustic structure of their calls sufficient to distinguish individuals and over time. Task 2 & 3: Quantitative, statistical and classification analysis of owl vocalizations

To determine the feasibility of using the vocalizations to identify the age, sex and/or individual identity of the vocalizer, a series of tests were conducted with the features extracted from calls and the corresponding raw sound files.

Three important criteria must be met for vocalizations to be valuable for demographic and population monitoring: it must be possible to detect and discriminate them automatically, and the discriminations must be statistically validated. Results of testing each criterion are given below.

5.2.1 Automated Detection

5.2.1.1 Approach

Automated call detection was conducted using call recognition software. The program ISHMAEL was developed by Dave K. Mellinger (NOAA/Pacific Marine Environmental Laboratory VENTS Program, Hatfield Marine Science Center, Oregon State University). It is available at http://www.pmel.noaa.gov/vents/acoustics/whales/ishmael/index.html. Although originally developed for passive acoustic tracking of whales, the software may be applied to any transient animal vocalization.

A representative signal (e.g., hoot note) was used as a template to match to the digitized recordings. The program detected calls (e.g., hoots, series) from the background of wind noise, bird calls, and other ambient sounds. Thresholds were set to optimize detection of signals matching the template.

Rates of call detection were collected using a second, independent method, the Praat 4.5 (Paul Boersma; www.praat.org) speech/phonetic analysis program. It detects, extracts and analyzes voiced or tonal portions of signals from background noise (Figure 2 below). It is also designed to track the fundamental frequency in a harmonic series. Spectral ranges and voicing/silence thresholds were optimized to detect signals within the specified frequency range.
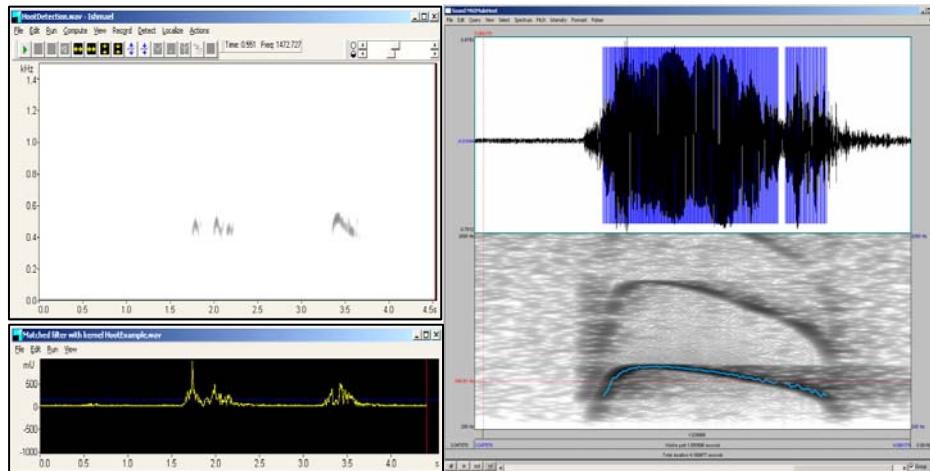
Figure 2. Representations of automatic detection in ISHMAEL (left) and Praat 4.5 (right). Note the detection window below the spectrogram on the left; it provides a visual representation of levels exceeding a threshold within a specified frequency range. The line in yellow above the blue threshold line is a detection event. It matches each hoot in the spectrogram. On the right, the blue line shows the Praat 4.5 time-frequency profile of the fundamental frequency of a hoot (one in a series of four).

5.2.1.2 Results

Calls detected using both ISHMAEL and Praat were compared against the list of calls identified by human listeners in the field. Detection rates of calls from the original sound files

estimated using the matched template feature in ISHMAEL ranged from 5%-96% (hoots: 83%, series: 96%, contact calls: 52%, barks: 41%, whistles: 5%). Lower detection rates for contact calls, barks and particularly whistles were the result of lower source amplitude and thus lower signal-to-noise ratio in recordings collected with omnidirectional microphones at practicable distances (10 – 50 m).

Because detection rates were low for contact calls, barks and whistles using the matched template approach, detections were re-conducted using Praat 4.5. Detections rates of calls using Praat 4.5 for these call types ranged from 53-81% (contact calls: 53%, barks: 73%; whistles: 81%), substantially higher than with ISHMAEL. Contact calls and whistles had consistently lower signal-to-noise ratio (SNR) due to low vocalization source level. Simple tracking of the fundamental frequency of these vocalizations in Praat was less sensitive to noise in the signal than matching to the entire call in ISHMAEL.

The results of the detection analysis described above were based on sound clips extracted by research staff from the larger sample of 121 hours of sound recordings. It showed that calls were detectable in relatively short clips of sound. A second analysis was performed to determine whether calls with high SNR, the four-note hoots and series calls, could be detected in sound files of longer duration with additional background noise. Although preliminary, the results were very promising. For three sound files containing long segments (>60 minutes) of recording from three adult males, detection rates using ISHMAEL ranged from 89%-100% (range of 9-42 calls per sound file with two false positive and no false negative detections).

5.2.1.3 Conclusion

The results of the detection analysis indicate that *four-note hoots and series call types are easily detectable from background noise* due to their high SNR. Contact calls and whistles may be difficult to detect in a field setting using a matched template unless the receiver is very close to the owls. These calls may be more readily detected using Praat 4.5 and then, once detected, classified into call types based on statistical analysis of acoustic features. Another perhaps better approach would be to use separate microphones for the different tasks being undertaken. For example, the signal from a directional microphone or a microphone placed in a nest might be used to collect the lower-amplitude vocalizations, resulting in a signal with higher SNR for the detection task. With such data, contact calls and whistles may be useful for sex, age and individual identification. If contact calls and whistles cannot be used for purposes of individual identification, they may be used to evaluate whether *an adult female or owlet is present at the in the activity center.* With appropriate correction for call frequency, these calls types are unique to their respective sex/age class.

Praat 4.5 performed better in the *detection* task under conditions of low SNR. However, there might have been significant errors in detection had overlapping of vocalizations from other species been present. The results of the Praat analysis sheds light on the calling behavior of the owls, which produce most of their calls in the hours immediately after dark and before dawn. During these periods, atmospheric conditions are still suitable for long-distance propagation, but diurnal and crepuscular bird species are silent. Under these conditions, calls with low SNR will be detectable at long range using only simple frequency-following algorithms. It can be

hypothesized that the owls optimize their behavior for detection at low SNR. This hypothesis will be discussed in more detail when sources levels of owl calls are described below.

5.2.1.4 Benefits

These data provide strong evidence that the presence of owls can be remotely and automatically detected using their vocalizations without need for deployment of field personnel for long periods. The development of a bioacoustic monitoring system could save substantial time and money while also enhancing the ability to effectively detect the presence of owls in activity centers during most of the year on military lands.

5.2.2 Call Discrimination

5.2.2.1 Approach

Calls detected in the previous analysis were entered into an analysis of call discrimination using automated methods. Praat 4.5 was used to extract a large number of spectral and temporal features from calls. Amplitude measures were not used in this analysis because the sample of calibrated recordings with good distance measurements was very small. Whole concatenated calls consisting of a series of hoots were analyzed as well as individual notes within calls. Concatenation is a procedure in Praat that extracts the "voiced" portions of calls. Using this method, all silences between the elements of a hoot were removed from the sound file prior to analysis (see top right graphic in Figure 2). Measures extracted from the concatenated signal included duration, minimum fundamental frequency, maximum fundamental frequency, mean fundamental frequency, standard deviation in fundamental frequency, position of peak frequency, position of minimum frequency, slope, jitter, shimmer and various measures of the harmonic-to-noise ratio (HNR). Some calls were determined to be of insufficient quality based upon the outcome of the acoustic analysis and were removed. These calls had inappropriate duration or were identified as "undefined" by the program.

Neural net analysis (pattern recognition analysis) on the remaining database of call features was conducted using NeuralTools 1.0 (Palisades Incorporated; www.palisade.com/NeuralTools). Cases for groups without sufficient sample size were removed before analysis. The data were broken into two sets for training and testing. For the training set, the efficacy of discrimination was determined by assessing percent bad prediction (the percent of cases for which the predicted category did not agree with the actual category determined by observers), mean incorrect probability (mean across all calls of a case-by-case error measure for category prediction) and standard deviation in the incorrect probability (standard deviation across all calls of a case-by-case error measure for category prediction). Outcome groups of interest were call type, sex and age, individual adult males, individual adult females and individual owlets.

The percent bad discrimination provided an estimate of how well calls were classified into groups. The mean and standard deviation of incorrect probability provided descriptive statistics across all calls, indicating the degree to which each sample call fitted into its

appropriate group. Percent bad predictions expected by chance were calculated using the formula: $p = 1-[1/\text{number of groups}]*100$. This measure represents the expected percent bad predictions if groups cannot be discriminated.

5.2.2.2 Results

The percentage of extracted calls that had sufficient quality after detection and acoustic analysis for use in pattern recognition ranged from 42%-91% (hoots: 53%, series: 91%, contact calls: 42%, barks: 69%, whistles: 81%). These calls were used for the subsequent neural net analyses.

Discrimination among the five call types. Percent bad prediction of the training data was 0.1% with a mean and standard deviation in incorrect probability of 3.2% and 6.9% respectively. Percent bad prediction by chance was 80%. Discriminant function analysis (Figure 3) shows that four-note hoots, barks, and series calls were differentiated from whistles and contact calls. Variables most responsible for distinguishing among call types were slope of frequency change, standard deviation in frequency, minimum frequency and median frequency.
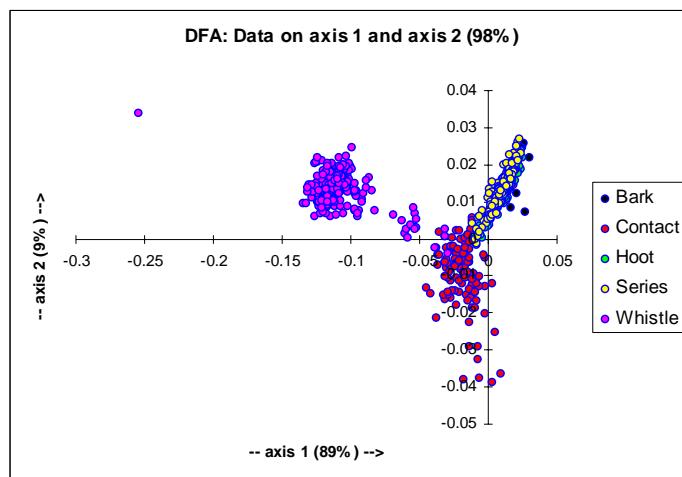
Figure 3. Discrimination of calls by call type. Note that whistles and contact calls are highly distinguishable from hoots, series and barks.

Discrimination among adult males and adult females using hoots and series calls. Percent bad prediction of the training data was 0.0% for discrimination of caller sex, with a mean and standard deviation in incorrect probability of 0.0% and 0.2% respectively. Percent bad prediction by chance was 50% (Figure 4). Variables most responsible for distinguishing among call types were mean frequency, median frequency, slope and shimmer (amplitude fluctuations in call).

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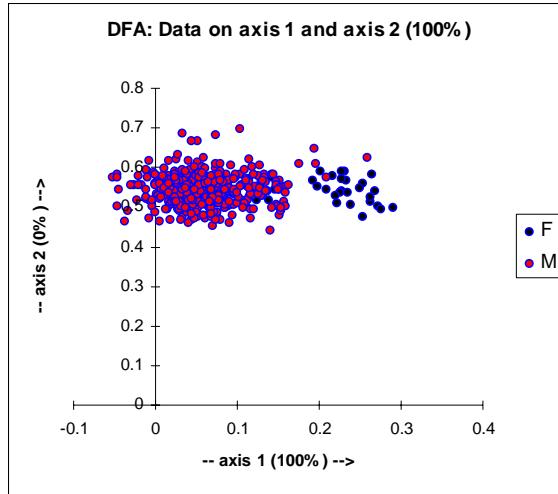
Figure 4. Discrimination of four-note hoots and series calls by sex of caller. Adult males and females were highly distinguishable based on acoustic features.

Discrimination of calls by sex *using* hoots and standard deviation in incorrect probability of 3.5% and 3.5% respectively. Percent bad prediction by chance was 66.7% (Figure 5). Variables most responsible for distinguishing among age-sex classes were slope of frequency change, standard deviation in frequency, mean HNR and maximum HNR.

Discrimination of calls by sex *and* age *using all* calls. The accompanying spectrograms show the major vocalization *types* produced by each age/sex class. Age-sex classes were highly distinguishable .

Discrimination among the adult male, adult female, and *owlet(s) in each territory using all* calls. Note the accompanying spectrograms of the major vocalization type produced by each age/sex class and that adult males, adult females and owlets are highly distinguishable from each other acoustically.

Discrimination among the adult males using all calls. Percent bad prediction of the training data was 0.0% with a mean and standard deviation in incorrect probability ranging from 0%-0.84%. Percent bad prediction by chance was 88.9%. Variables most responsible for distinguishing among males were median frequency, jitter (frequency fluctuations in call), standard deviation in HNR, and slope of frequency change.

Discrimination among individual adult males using all calls. Percent bad prediction of the training data was 0.0% with a mean and standard deviation in incorrect probability of 4.9% respectively. Percent bad prediction by chance was 90%. Variables most responsible for distinguishing among males were median frequency, jitter (frequency fluctuations in call), and slope of frequency change.

Discrimination among individual adult males using all calls. Percent bad prediction of the training data was 0.0% with a mean and standard deviation in incorrect probability of 0.85% and 8% respectively. Percent bad prediction by chance was 66.7%. Variables most responsible for

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distinguishing among males were median frequency, mean frequency fluctuations in HNR, and mean HNR.

Discrimination among individual adult males using all calls. Percent bad prediction of the training data was 0.0% with a mean and standard deviation in incorrect probability of 0.25% and 1.49% respectively. Percent bad prediction by chance was 75.0%. Variables most responsible for distinguishing among males were mean frequency, standard deviation in HNR, and mean HNR.

Discrimination among individual adult females using contact calls. Percent bad prediction of the training data was 0.0% with a mean and standard deviation in incorrect probability of 0.0% and 0.0% respectively. Percent bad prediction by chance was 66.7%. Variables most responsible for distinguishing among females were, mean HNR, median frequency, standard deviation in HNR and mean frequency.

Discrimination among individual owlets using whistles. Percent bad prediction of the training data was 0.0% with a mean and standard deviation in incorrect probability of 0.25% and 1.49% respectively. Percent bad prediction by chance was 85.7%. Variables most responsible for distinguishing among owlets were mean HNR, median frequency, slope of frequency change, and mean frequency.

5.2.2.3 Conclusion

The results of the neural network analysis across call type, age-sex class, and individual indicate that call discrimination was excellent at multiple levels in Mexican spotted owls. The major call types (hoots/series, contact calls, whistles) were easily discriminable by automated means, as were age and sex of the owls. The data also supported the hypothesis that individuals could be discriminated. Adult males could be discriminated using all calls as well as hoots and series calls. Adult females could be discriminated using all calls as well as contact calls alone, as long as the sampled calls had sufficient signal-to-noise ratio. Owlets could also be differentiated by whistle calls, although the interpretation of these data were more difficult because individual owlets could not be identified.

5.2.2.4 Benefits

The results of the neural network analysis provide strong evidence that automated classification of vocalizations is practicable in the Mexican spotted owl. Based on the preliminary dataset available during this analysis, a bioacoustic monitoring system could be designed to effectively count individual owls in each sex class and determine the presence of owlets at nesting sites, thereby signifying reproductively successful pairs. Thus, acoustic techniques have the promise to remotely characterize the demographics of owl populations but also estimate reproductive success.

5.2.3 Statistical Validation

5.2.3.1 Approach

      Additional neural net analyses were conducted for several outcomes on the testing datasets (usually ≥25% of the entire dataset). They were used to validate performance of neural network analysis, particularly to determine whether new calls from known individuals would be discriminated reliably by the neural net. The efficacy of discrimination was determined by assessing the percent bad prediction of the testing set for a number of outcomes: call type, sex and age, individual adult males, individual adult females and individual owlets.

5.2.3.2 Results

Discrimination among the five call types. Percent bad prediction of the testing data was 7.9 % with a mean and standard deviation in incorrect probability of 12.7% and 24.1% respectively. Percent bad prediction by chance was 80%. Bad predictions were mostly due to the misclassification of barks and series calls to the hoot category. Both of these calls are highly variable, so the result is not surprising. More stereotyped hoots, contact calls and whistles exhibited less than 7% bad predictions.

Discrimination among adult males and females using hoots and series calls. Percent bad prediction of the testing data was 0.8% with a mean and standard deviation of incorrect probability of 1.1% and 9.1% respectively. Percent bad prediction by chance was 50%.

Discrimination among adult males, adult females using all call types. Percent bad prediction of the testing data was 6.7% with a mean and standard deviation in incorrect probability of 7.8% and 9.1% respectively. Percent bad prediction by chance was 66.7%.

Discrimination among adult male, adult female and owlets) in each territory using all call types. Percent bad prediction of the testing data was 6.7% with a mean and standard deviation in incorrect probability of 7.8% and 22.4% respectively. Percent bad prediction by chance was 66.7%.

Discrimination among the adult males using all calls. Percent bad prediction of the testing data was 12.5% with a mean and standard deviation in incorrect probability of 0%-6% respectively. Percent bad prediction by chance was 88.9%.

Discrimination among individual adult males using all calls. Percent bad prediction of the testing data was 15.2% with a mean and standard deviation in incorrect probability of 18.0% and 31.1% respectively. Percent bad prediction by chance was 90%.

Discrimination among individual adult males using all calls. Percent bad prediction of the testing data was 2% with a mean and standard deviation in incorrect probability of 3.4% and 16.8% respectively. Percent bad prediction by chance was 66.7%.

Discrimination among individual adult males using all calls. Percent bad prediction of the testing data was 7% with a mean and standard deviation in incorrect probability of 9.2% and 26.4% respectively. Percent bad prediction by chance was 83.3%.

Discrimination among individual adult females using all calls. Percent bad prediction of the testing data was 3.6% with a mean and standard deviation in incorrect probability of 3.6% and 18.6% respectively. Percent bad prediction by chance was 66.7%.

Discrimination among individual owlets using whistles. Percent bad prediction of the testing data was 3.6% with a mean and standard deviation in incorrect probability of 3.6% and 43.6% respectively. Percent bad prediction by chance was 85.7%.

The analysis showed that effective and consistent results were dependent on adequate samples of calls from each individual. A regression of *sample size of the training set* against *% bad prediction in the testing set* reveals that a larger training set allows for better predictions in the testing set ($t_{11} = -2.53$, $p < 0.03$) (Figure 6). Optimal sample sizes were on the order of 50 or more calls per individual.
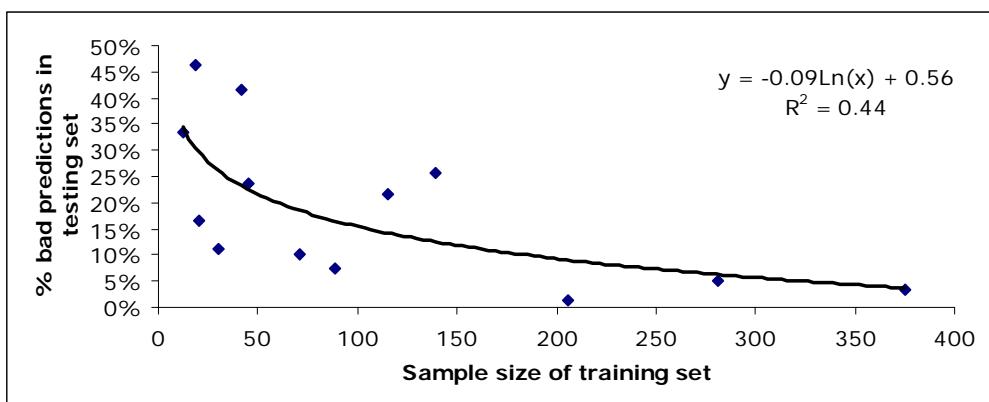
Figure 6. Regression of sample size of training set against % bad predictions in testing set.

5.2.3.3 Conclusion and Benefits

The percentages of bad predictions in most tests during the validation phase were very low (less than 16%), and in all cases were significantly and substantially lower than expected by chance. The results were particularly encouraging considering that samples were collected opportunistically, and were therefore unequal among individuals both within and among years. These multi-year vocalization data on individual owls therefore provide an excellent indication that vocalizations represent a valuable tool for automated and remote tracking of individual and population parameters, particularly the sex and age of owls in each territory and presence of young. It is also likely that adult owls can be tracked. However, success of remote monitoring will be dependent on finding methods for collecting adequate samples of calls (> 50 calls) at relatively close range from each territory, preferably within year. During the ACC/CEVP study,

turnover of adult owls was probably low, but could not be monitored because birds were not banded. Mexican spotted owls have high territory and mate fidelity, but at least four pairs were known to have experienced turnover during the study (Bowles, unpub. data), and other undetected changes could have occurred.

5.3 Aim 1 & 2: Determining whether Mexican spotted owls exhibit systematic variation in the acoustic structure of their calls sufficient to distinguish individuals and over time. Task 3: Development of pattern recognition program for acoustic signature analysis

Neural network analysis does not yield an explicit characterization of the criteria by which calls are classified into types. To determine which features could have permitted classification, a CART analysis was also conducted as described below. The results can be used to design a pattern recognition program for Mexican spotted owl vocalizations.

5.3.1 Approach

Based on the post-hoc examination of training dataset size against percentage of bad predictions, the sample sizes for the training and testing sets by individual for multiple individuals were not adequate. Therefore, a reliable set of classification algorithms could not be developed for individual owls using the CART approach. Based upon the successful results obtained in the neural net analysis for Task 2, the researchers are confident that once sufficient sample sizes are obtained, this method will be applicable to individual owls. Data for classification by age and sex were adequate, however, and the CART analysis was pursued.

The CART analysis uses a binary decision tree based on previously described acoustic measures of vocalizations to explore and partition a complex multivariate data set into simple classification groups. CART trees were generated using S-Plus 6.0 (MathSoft Inc.; www.insightful.com). The method is particularly well suited for this task because it is distribution is independent and therefore capable of successfully working with data that deviates strongly from well-described distributions (e.g., multi-modal or irregular distributions). The acoustic variables used in the analysis were not normally distributed, nor did they fit other common distributions.

The decision tree generated by CART makes binary decisions at each node, so statistical criteria are needed for deciding which variable will be used at each split in the tree. At each split, the variable is identified that allows a hyperplane decision boundary orthogonal to the coordinate axes to split the data into the purest groups (Duda et al. 2001). This is based on the decision rule described by Venables et al. (1999). Purity at nodes of the tree is more easily calculated as *impurity*, and S-Plus calculates this as deviance for the tree (Venables et al., 1999), defined as *D*, where

$$D = \sum_i D_i, \qquad D_i = -2\sum_k n_{ik} \log p_{ik}$$

Deviance is summed over the "leaves," or current terminal nodes, of the tree. For each permutation of the decision rule, each leaf has a random sample n_{ik} from the multinomial distribution specified by p_{ik}. Since deviance resulting from the previous split will be established

for the tree, the choice of variable to be used for the next split can be the one that brings the greatest reduction in deviance for the tree overall (Duda et al., 2001; Venables et al., 1999).

At many splits in the tree there will be overlap of the probability distribution of the classes, so there will be no partition that will completely describe all classes. If have deviance measures greater than zero, Bayes decision rules are used to choose the category represented at each leaf (Venables et al., 1999).

CART analysis was applied to the dataset of owl vocalizations. Of the 961 vocalizations used in the analysis, 12 were female barks, 43 were male barks, 55 were female hoots, 303 were male hoots, 152 were male series hoots, 116 were female contact calls, and 280 were owlet whistles.

5.3.2 Results

The CART method generated a tree that used nine of the 14 variables extracted using Praat to classify groups. These were slope of frequency change, mean F_0, minimum F_0, minimum HNR, minimum frequency position, maximum HNR, peak position, jitter, and standard deviation of HNR. Eighty percent of the data were used as a training set for creating the decision tree and 20% of the data were used to test the success of the resulting tree. The minimum number of samples in a category before a split could be considered was 5 (this prevented an overfitted tree), and the minimum node deviance before growing stopped was 0.01.

The misclassification rate for the training set was 2.08% or 16 out or 769 recordings. Figure 7 shows an intuitive depiction of the classification tree generated by S-Plus indicating the variables used in each split and the threshold for that split.

Decision Tree for Classification of Mexican Spotted Owl Vocalizations by Nine Acoustic Variables
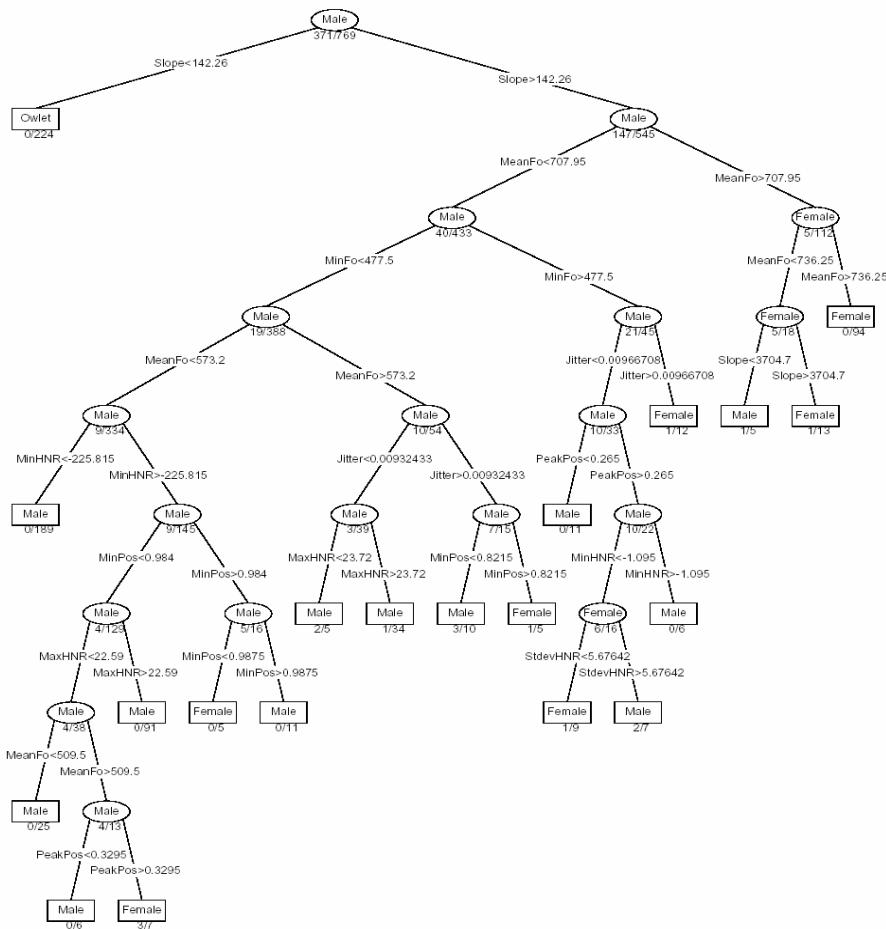
Figure 7. Classification tree of Mexican spotted owl vocalizations by sex and age class. Results shown are from the training data set. The ratio m/n below the boxes indicates the proportion of training cases reaching that node incorrectly (m = errors, n = sample remaining in the training set). Tree splits indicate the variable used and the threshold in value for making a split. (Variable codes: Slope = Slope, Mean Fo = Mean frequency, Min Fo = Minimum frequency, Jitter = jitter, MinHNR = Minimum harmonic-to-noise ratio, MaxHNR = Maximum harmonic-to-noise ratio, StdevHNR = standard deviation in harmonic-to-noise ratio, PeakPos = Percentage of call duration at which the maximum frequency occurs, MinPos = Percentage of call duration at which the minimum frequency occurs).

The model tree created using the training data performed well on the testing data. The error rate for classification was 10.42% or 20 out of 192 recordings.

A highlight of this classification scheme is that accuracy can be improved by being selective about the types of vocalizations used in the analysis. For example, initial analysis of the variables showed a significant overlap in distribution of acoustic features of barks by adult female and male owls. This was borne out in the CART analysis. In the testing set, three of the

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four female bark recordings were misclassified as males. Future automated classification schemes could include algorithms for excluding calls that are less distinguishable, such as barks, from analysis.

5.3.3 Conclusion and Benefits

CART analysis was successfully employed to develop a classification pattern recognition algorithm that sorted vocalizations into appropriate age and sex classes. Further development of these and other algorithms along with a substantially greater sample size would allow us to develop a stand-alone computer program to classify first between age and sex classes and then within each age and sex class by individual. With this information, activity center occupancy and presence of young and individual adult male and female owls could be determined.

As a part of the ACC/CEVP study from which the vocal recordings used in this project were obtained, additional data were analyzed to assess whether owls produce sufficient source levels and are sufficiently vocal within preferred activity centers to permit adequate samples of calls to be obtained by automated listening stations. These data are presented in a separate report entitled "Level and Rate of Mexican spotted owl Vocalizations in the Gila National Forest, 2000 - 2005" (see Appendices).

6. Conclusions

Each of the specific aims and tasks outlined in this project were successfully accomplished. The results showed that adequate sample size is a key but achievable need for further development of this technology. Collection of the data opportunistically during monitoring surveys probably will not yield adequate data based on the experience obtained during the ACC/CEVP study. Thus, automated recording stations should be developed.

Although the sample sizes were insufficient to develop a set of classification algorithms for individual owls, the results presented in Task 2 provide ample evidence that once sufficient sample sizes are obtained algorithms can be successfully designed and eventually implemented in a stand-alone pattern recognition program. Owls could be classified not only by sex and age class but by individual.

The utility and economic feasibility of developing automated recording technology is substantial. If coupled with some type of localization array, all the information collected during protocol-based surveys (USFWS 2003) and banding studies could be obtained.

Development and transition to an automated acoustic monitoring system is described in Future Directions below. The data would provide the following estimates on Mexican spotted owl populations on military lands:

6.1 Estimation of population patterns and yearly territory occupancy

The data analyzed here were obtained by observers on foot. The time required to access the site and collect the data was considerable. There was also substantial disturbance introduced. Both problems prevented frequent access to any given activity center to collect data, and observers were usually only able to collect a few calls per visit. Usually, the owls were moving in response to observers. Thus, the method for collecting data would not be practical, even if a dedicated study were planned. The only practical alternative would be to install long-term acoustic monitoring stations, preferably including a small array that could be place around the nest site to localize callers. Although the stations would necessarily be fixed, the results of the sound level meter analysis reported in Appendix I*** show that automated recordings would perform at least as well as recordings by observers, and could be made in or near the nest without unacceptable disturbance.

Automated stations would be able to detect the presence or absence of a defending male (based on male four-note hoots), an attending adult female (using female contact calls) and whether the pair has been successful in producing one or more offspring (using owlet whistles) in each activity center (Figure 8). If individuals can be distinguished, individual population parameters can be obtained as well. These data can be used to provide population estimates for adult males, females and owlets on military lands on a yearly basis as well as the short-term and long-term patterns of use of each territory and pair productivity.
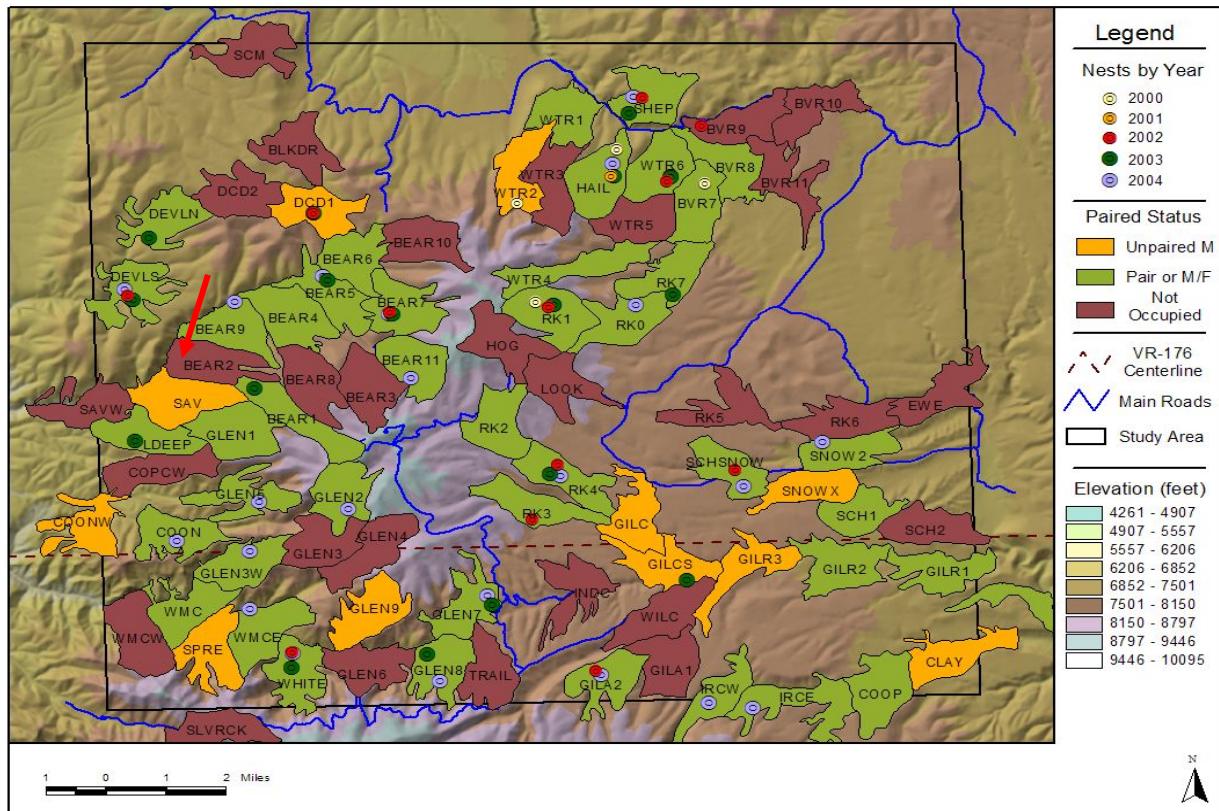
Figure 8. Graphic of the territories in the study area. Boundaries include both PAC polygons in cases where the territory has been formally recognized by USFWS (e.g., BEAR2 indicated by red arrow);and estimated usage areas for territories discovered for the first time during the ACC/CEVP study colors represent the pairing status of owls defending the territory (unpaired adult male, paired adult male, unoccupied); approximate nesting sites by year are indicated by filled circles.

6.2 Tracking of Yearly Activity Center Occupancy by Individual Adult Males and Females

Use of hoot and series calls for adult males and contact calls for adult females to individually identify *which* adult male and *which* adult female are present in each territory on military lands on a yearly basis. For new individuals entering the population, the neural net, CART or other approaches can be designed to sort unrecognizable calls from a territory into a call type category (hoot/series, contact calls, whistle) and then to its own new individual type. If

there is potential for the hoot/series data to be from either an adult male or an adult female in a territory. these calls will be differentiated based upon known sex differences in acoustic structure. As data are collected from new individuals over the season, the neural net will be trained to include these new individuals each as its own category in order to identify the individual in future seasons. This feature is valuable because specific individuals will be identifiable to examine longitudinal changes in the demographics of owl populations, such as patterns of immigration and emigration, on military lands.

6.3 Sexing of Owlets

Preliminary data on the clustering of whistle calls indicates that there are two distinct clusters of whistles (Figure 9). Field observers found that individual owlets produced one call type or another, suggesting that the difference may be sex related. This is a promising avenue of future research. Although it would initially require collection of recordings from marked owlets, if the sex difference can be confirmed, this tool would provide a noninvasive method for sexing young at banding, a valuable tool for a detailed examination of owl demographics on military lands.

These two components explain 48.06 % of the point variability.
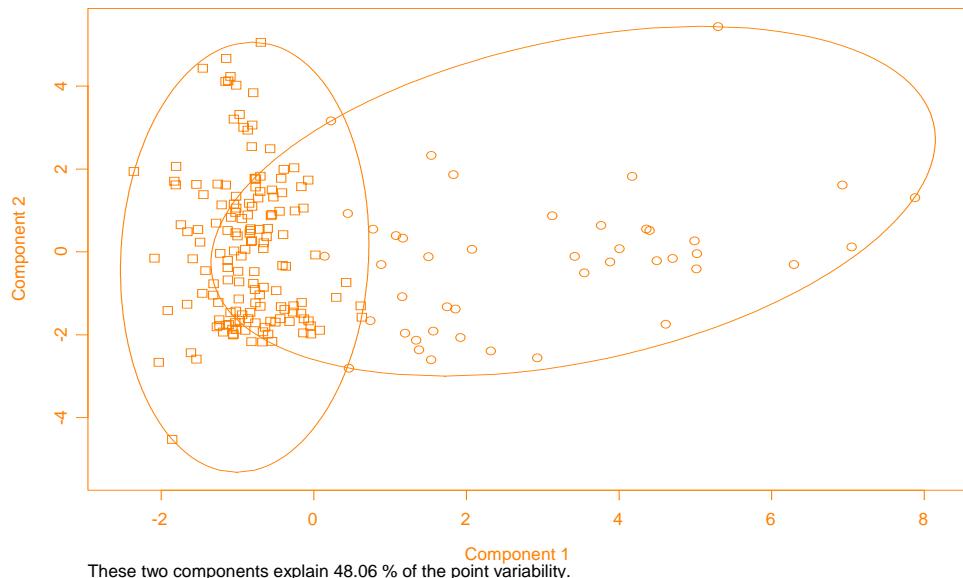
Figure 9. Cluster analysis on owlet whistle measurements indicating the presence of two distinct clusters. Future research will determine if this distinction is a result of a sex difference in order that vocalization can be used as a noninvasive method for sexing owlets at the time of banding.

7. Future Directions

The goals of the acoustic monitoring effort during the ACC/CEVP research that provided data for this feasibility study were (1) tracking of military aircraft and (2) determination of a noise budget for anthropogenic and natural sound sources in the study area. Therefore, the configuration of the acoustic monitoring array, sampling protocol, and efficiency of data collection were not optimal for an acoustic survey of owls. However, the results of the study do suggest characteristics of a more efficient automated acoustic monitoring effort that has a high potential to provide efficient monitoring of Mexican spotted owls over long periods and large areas. Future studies that are envisioned will have three components designed to overcome the technical challenges that have been identified during this feasibility study.

7.1 Component I. Owl Identification

Current survey protocols for Mexican spotted owls assume that owls occupy confined territories and that they exclude conspecific neighbors from these territories effectively. They also assume that pairs are not moving between territories. Although Mexican spotted owls certainly exhibit high territory fidelity, the results of the study in the Gila National Forest (Bowle unpub.) clearly indicate that neighbors challenge one another's boundaries, that non-breeding 'floater' owls sometimes respond to acoustic lure surveys, and that environmental and reproductive context greatly affect owl usage of both activity centers and the foraging areas around them. Tracking studies reviewed in USFWS (1995) support these observations. In particular, although the nominal activity center protected for a given Mexican spotted owl pair is approximately 247 ha in area, they are known to use much larger areas, particularly under poor conditions (territories of over 1500 ha have been documented).

Unfortunately, individual Mexican spotted owls currently cannot be tracked and monitored over long periods of time efficiently. Radio-tracking studies have resulted in significant mortalities in the past and are strictly limited to eliminate possible population effects (USFWS 1995). Owls may be safely equipped with leg bands, but monitoring of banded bird movements is extremely labor-intensive. Therefore, it is both expensive and dangerous to mark and track large numbers of individuals over long periods. Long term population monitoring will never be accomplished over large areas in this way. The first goal of the proposed study will therefore be to mark a small number of individuals under permit and to collect a usable sample of territorial calls from these individuals over a period of at least three years to further and more directly evaluate the stability of calls as a source of individual information. The small sample of calls collected within year during the ACC/CEVP study prevented examination of between year differences under Tasks 2 and 3 of this initial study.

These data must be collected by observers trained to work around owls (under USFWS permit) and to collect real-time recordings with calibrated systems to ground-truth the automated recordings.

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7.2 Component II. An Automated Acoustic Array for Individual Monitoring

Based on the experience in the Gila National Forest, recording instruments suitable for collecting individual owl calls must have the following characteristics:

1. At least one microphone and recorder placed in the center of an activity center, possibly with the microphone within a few meters of the territorial nest

2. Microphones must have as many of the following characteristics as possible:
    a. a low noise floor (10 dB sound pressure level [SPL] or lower)
    b. at least 96 dB of dynamic range
    c. weather resistant microphones with at least 5 cm of windscreen coverage
    d. if directional microphones are used to collect owl vocalizations for individual analysis, the station must include one calibrated omni-directional microphone that can be used to estimate source levels
    e. frequency range from 20 Hz to at least 10 kHz
    f. frequency and amplitude stability under varying environmental conditions (-10°C to 45°C, in the presence of electrical storms and heavy rain)

3. Recording systems must have the following characteristics:
    a. the capacity for continuous recording during the periods from 18:00 to 21:00 and 03:00 to 0600 daily over a four month period; overnight recordings are preferable
    b. capacity to store real-time samples at least during periods when owls may be calling
    c. long servicing intervals
    d. a power source that performs efficiently under 60% forest cover
    e. high-capacity on-board storage disk/drive or capacity to send data via telemetry to a remote site
    f. high reliability - the unit must operate nearly continuously for periods of at least 15 days (8 servicings per season)
    g. a housing hardy enough to withstand trampling or attack by cattle, elk, bears, rodents and raptors
    h. good camouflage to prevent detection by predators

4. Software must be developed from the methods described in this report as well as the exploration of other approaches to detect calls and identify individuals (see below).

In order to collect the data needed, units must be deployed in Mexican spotted owl activity centers close to owl nests and roosts. Preferably, the microphone(s) dedicated to recording of vocalizations will be mounted at nest or roost level within a few meters of the next. It may be necessary to use multiple microphone/recording stations to perform the three functions desirable (collection of owl calls, call localization, estimation of source level).

7.2.1 Software Development

As described above, in order to further develop this technology and transition this technology for use on military lands, the following are envisioned:

1. Conduct systematic acoustic recordings to substantially increase sample size of individuals to enhance further algorithm development;

2. Further expand and refine algorithm development for identifying individual owls, sexing owlets and adjusting for topographical distortion by pursuing methods described in this report (neural net, CART) as well as other new and innovative approaches borrowed from the study of pattern recognition of visual signals; and

3. Develop a stand-alone remote automated system for owl vocalization collection, processing/detection, encoding, and classification.

The setup of remote automated long-term recording units as described above at the nesting site of each territory during each breeding season across multiple seasons will allow us to obtain sufficient sample sizes of calls for development of pattern recognition algorithms for detecting and tracking individual owls and sexing owlets.

7.2.2 Algorithm Development

Once sufficient sample sizes are collected, algorithm development will continue for the classification of individual owls in each sex and age class and for sexing owlets. The researchers will continue to pursue the approaches outlined in this final report (CART and neural net) but will also pursue other new and innovative approaches borrowed from the study of pattern recognition of visual signals (see below) in collaboration with Dr. David Warland, of UC Berkley, an expert in this area of research.

7.2.3 Design of a remote automated software system for detecting and localizing owls

To develop the system for remote automation, there are three components to that will need to be developed: (1) a preprocessor or detector that will de-mix and de-noise the field recordings, (2) an encoder that will represent the signals in a basis optimized for owl vocalizations, and (3) an analyzer that will characterize the "acoustic texture" of the vocalizations for use in identifying individual owls.

Preprocessor/Detector

Field recordings typically contain many other sounds besides the vocalization of an individual owl such as road noise, wind, other animals etc. If these non-owl acoustic signals are not removed prior to analysis, they may prevent or interfere with proper identification and analysis. The results on the automatic detection of owl vocalizations as presented in this final report indicate that automatic detection of owl vocalizations will be reliable for most call types, especially for vocalizations recorded in close proximity to the acoustic stations (also see report in Appendix). However, to ensure that accurate detection is maximized, the use the recent state-of-the-art algorithms for "blind source separation" (de-mixing) will also be explored by exploiting higher-order statistics of the owl calls (Lee et al., 2000; Lee et al.; 2006; Suruwatari et al.; 2006). One practical insight from this blind source separation work is that multiple microphones greatly improve the performance of the algorithms. In addition, these algorithms have been shown to

work well even in reverberant conditions such as found in canyons (Kim et al.; 2006). To determine how important this is for the current study, field recordings using multiple microphones will be acquired and the performance (i.e. SIR Signal Interference Ratio) of the algorithm as a function of the number of microphones will be determined. This result will guide how future field recordings will be performed and processed. While simply decomposing the signal into its various sources can de-noise a signal, often, additional sources of noise remain in the separated source. Drawing on techniques from visual signal processing, higher-order statistical models of the vocalizations will be used to perform Bayesian de-noising (Simoncelli; 1999). These statistical models are built from the results from the next two components of the system: the encoder and analyzer.

Encoder

In addition to the types of acoustic parameters used in this project to successfully distinguish the sex, age and identity of owls, the use of tools borrowed from the study of sensory processing will also be explored. In recent years there has been accumulating evidence that the brain forms sparse representations of sensory data (Olshausen and Lewicki; 2001; Olshausen, 2003; Olshausen and DJ, 2004). One speculation is that these sparse representations facilitate the forming of associations and the storage of patterns in neural networks at higher levels of representation. In vision, recent computational modeling studies have shown that when a set of basis functions is adapted to natural images so as to form a sparse representation (only a few coefficients are need to represent the signal), one obtains receptive field structures similar to those found in the primary visual cortex of mammals (Olshausen and Field, 1996). These methods have been extended to the study of efficient coding of natural sounds where it was found that the resulting basis functions resemble the tuning of auditory nerve fibers (Lewicki, 2002). Drawing on this work, the isolated owl vocalizations from the preprocessing stage above will be used to learn a sparse representation in which the second order statistical dependences are minimized between the learned basis functions. The coefficients of the vocalizations when represented in this optimized basis set will be further analyzed for their higher order statistical dependencies (Karklin and Lewicki, 2003).

Analyzer

In addition to the CART and neural net approaches described in this report, the investigators will also explore the use of linear coefficients generated by the encoding step described above. After the owl vocalizations have been encoded using the linear basis set, the probability distributions of the coefficients can be fully characterized. These distributions then form a statistical model of the call (e.g., if coefficients were drawn from these probability distributions and then applied to the owl basis set, the resulting waveforms would sound like owl vocalizations). Similar analysis has been performed using visual textures with stunning success (Portilla and Simoncelli, 2000). Instead, here the acoustic "texture" of the owl's vocalization will be characterized by the distribution of the coefficients to identify individual owls within each sex and age class.

7.3 Component III. An Automated Acoustic Array for Population Monitoring

The equipment required to collect individual owl vocalizations may not be useful for conducting an exhaustive survey of owls in an area. First, deployment in activity centers will necessarily reduce the receptive range of the instruments because most nesting and roosting areas are well down on steeply folded slopes. Surveys conducted in drainages typically detect owls only at ranges of 250 m or less (Bowles, personal observation). Instruments intended to localize callers would have more effective reception ranges if they were deployed at sites with good coverage of both the activity center and foraging areas. At these sites, the instruments would not obtain data suitable for identifying individuals, but would be very effective at detecting MSO at ranges of at least 400 – 800 m.

The information needed to conduct surveys is simple - range and preferably bearing to callers. It could be obtained in two ways. First, the instruments could be calibrated so that absolute levels could be measured and range could be estimated from these data. Alternatively, arrays of three or more instruments could be used to localize callers using a combination of level, time-of-arrival, and spectral information. Sparse, distributed arrays of this kind with good frequency and amplitude stability have been used to localize marine mammals underwater with moderately good resolution (30° or less) and are now being tested for terrestrial applications as well.

The success of the development effort will depend on access to a known population of owls. The dense population in the Gila National Forest study site (an estimated 41 pairs in a 485 km^2 area) would be suitable because the population in the area has been mapped extensively over a 6-year period and there is good logistic access.

During this component of the project, an array with the following characteristics would be developed:

1. Details of the choice of localization method (array-based, use of calibrated instrumentation must be part of a focused effort during the first year of the study).

2. Each occupied area would be covered by an array of three or more elements distributed in a triangle 400 m on a side centered on the activity center centroid.

3. Additional individual elements could be placed in areas not known to be occupied by owls.

4. The noise floor of the instruments should be as low as possible; 10 dB SPL or lower would be ideal.

5. The instruments must be designed to collect data continuously at night (18:00 to 06:00) throughout a four month period.

6. Software must be developed to detect calls, localize callers, and estimate range under these more wide ranging monitoring conditions. Some of the methods employed for individual monitoring may be applicable here (see section 7.2 above).

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Appendices

List of Technical Publications

None currently

Other Technical Material

None

Supporting Data (follows)

1) Technical Report: Level and Rate of Mexican spotted owl Vocalizations in the Gila National Forest, 2000 – 2005.

2) Technical Data: Classification tree output from S-Plus on age and sex categories.
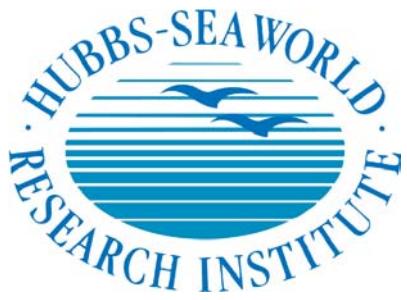
Level and Rate of Mexican Spotted Owl Vocalizations in the Gila National Forest, 2002 - 2006

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Level and Rate of Mexican Spotted Owl Vocalizations in the Gila National Forest, 2002 – 2006

Introduction

Mexican spotted owls (MSO) prefer old-growth conifer forests in steep, heavily folded terrain at moderately high elevations (Gutierrez et al. 1995). They maintain their territories and contact mates and young through the use of vocalizations. The most useful of these calls is a four note hoot produced by the territorial male, predominantly in the evening and just before daybreak (Forsman et al. 1984). These calls could be recorded at fixed locations because MSO exhibit very high fidelity to roosting and nesting areas within season and often use the same areas from year to year. Acoustic surveys are already an important tool for monitoring and locating these owls, but the calls have greater even potential as a signal for censusing individuals and determining reproductive status. However, to use them effectively as a censusing tool, it will be necessary to estimate the range at which they can be recorded with sufficient signal-to-noise ratio (SNR) for detection and individual identification. This information will be particularly important if automated censusing systems are to be developed. To date, there has been no exploration of the source levels produced by MSO or the rate at which their calls can be recorded from fixed monitoring stations in their preferred habitat.

To obtain preliminary measures of both, data from a 6-year study of MSO in the Mogollon Range, Gila National Forest, New Mexico, were examined (Bowles unpub.). Calibrated vocalizations of MSO were collected in two forms. First, real-time data were recorded by observers within approximately 100 m of calling owls using a calibrated recording system. These data were used to characterize calls and estimate source levels. Additionally, recording sound level meters were used to monitor all sounds in owl habitat around the clock during the breeding season. Time-history profiles of owl vocalizations were recognizable in these data and could be used to estimate the rate at which MSO could be detected from fixed stations.

Methods

Real-time Recordings

Real-time owl vocalizations were collected using calibrated using a Tascam digital audio tape (DAT) or Sony digital audio (DA) recorder equipped with an ACO 7013 0.5 cm microphone. Microphones were mounted at 1.4 m above ground level on a tripod and covered with a 10-cm open-pore foam windscreen. A calibration tone was recorded before the start of each recording session using an LD CAL200 calibrator. Both systems had a frequency range of 20 Hz to 20 kHz and dynamic range in excess of 76 dB. System gain was set so that the calibration tone was at the upper end of the linear part of the dynamic range. The gain setting was prevented from movement after calibraton by setting an adjustment screw (DA systems) or taping the potentiometer in place (DAT systems). A second calibration tone was laid down at the end of each recording session

to ensure that a shift in gain during the recording system could be detected. If a change was detected, the recording was not used to obtained source levels (SL). Absolute recording time was laid down on the recorder's time track at the start of each session using a satellite clock. This enabled staff to synchronize real-time recordings with the data on their GPS units and any nearby SLMs.

Teams of two observers collected recordings during monitoring efforts designed to assess reproductive status. Owls were located by approaching known activity centers on foot an hour before dusk or at dawn. One observer was designated as the sound recordist, while the other was responsible for collecting monitoring data. These approaches were conducted by observers trained using U.S. Fish and Wildlife Service protocols for monitoring (USFWS 2003). The observers typically emitted four-note hoots at 1 min intervals 50 – 100 m from the area where owls were thought to be roosting. Occasionally, owls began to call spontaneously when observers came into the area, in which case the observers did not call in return. In every case, they emitted the smallest number of calls possible and, once the owl began calling, did not begin calling again unless they lost track of it. When the owl responded, the sound recordist approached slowly and quietly, placing the microphone stand on the ground, and waited until further calls were emitted. The other observer assisted in determining the distance between the owl and the microphone, owl orientation, and perch height.

Owls typically called for a few minutes (< 15 min) from a given location and then moved. When they moved, the recordist followed and selected another station. Locations were recorded using a GPS unit. Distances to owls were determined using a range-finder when owls remained stationary and light conditions permitted, but range and bearing often had to be estimated by eye or ear. Distance estimates were not accepted unless observers were confident of the accuracy of the measurement (i.e., they were able to see the owl, or heard it at close range and with no significant obstructions). At relatively close ranges (< 100 m), an experienced observer could make these estimates to within a few meters. The orientation of the owl relative to the microphone was recorded whenever it could be seen.

To prevent undue disturbance, nesting owls were not recorded until after the young had reached thermal independence. They were not recorded during adverse weather conditions (snow and rain), when it was windy (wind speed greater than 16 kph), or when predators such as great horned owls (GHO) were known to be in the area.

When owls were recorded from multiple locations, individual source levels could be estimated. Source levels (SL) were obtained by regressing the data against a simple spherical spreading model ($L_{max} = SL - 20*\log_{10}[Distance]$). A more approximate 'population' model was obtained by regressing calls from multiple individuals at varying distances. The fit of the model was optimized using a least squares fit and the regression was tested using ANOVA. The range of possible SL values was estimated using 95% confidence limits.

Time-history Data from Sound Level Meters

From 2002 to 2006 continuous time-history data were collected using an array of 39 Larson-Davis (LD) sound level meters (LD 820, LD 824 SLMs) in the study area. SLM stations were deployed in the vicinity of nesting and roosting areas, referred to as activity centers, throughout the 20 km x 24 km area. To reduce disturbance in activity centers when the stations were maintained, SLMs were placed several hundred meters from them, but on the same slope and at the same level relative to drainages and ridges

SLM microphones (B&K 4176) were mounted on a 3-m galvanized steel pole and equipped with a 10-cm open-pore foam windscreen to reduce mechanical wind noise. They were calibrated at the start and end of each monitoring period with an LD CAL200 calibrator that produced a 1 kHz tone at 94 dB. The system had a frequency range of 7 Hz to 12.5 kHz and a dynamic range of 14 dB to 142 dB.

The sound level meters sampled sound at a rate of 20 kHz and recorded an A-weighted level every 31 ms. The signal was A-weighted, which ensured that sounds throughout the hearing range typical of birds (125 Hz to 8 kHz) were collected, but that low-frequency noise produced by wind did not contaminate levels. SLMs were adjusted to collect equivalent-continuous sound levels every two seconds (L_{Aeq2s}), expressed in units of $\mu Pa^2 \cdot s$, a measure of the sound energy during the sampling interval. The two-second interval was chosen to ensure that data were sufficiently compressed to allow instruments to collect data nearly continuously throughout the season, while still providing sufficient detail to allow sound sources typical in the study area to be identified (e.g., regional commercial jet traffic and birds). Instruments also collected the sample with the highest sound pressure level (RMS SPL) during each period. The LD 824 instruments collected an averaged unweighted 1/3-octave band spectrum every 30 s to allow spectral information to be obtained.

Owl vocalizations were identified in the recordings during the period between dusk and dawn. The time-history profile of a calling bout appeared as a series of constant-amplitude peaks occurring at regular intervals, in which individual hoots appeared as a single peak (Figure 1). Vocalizations of the two large species (MSO and great horned owls [*Bubo virginianus*] [GHO]) were distinguishable from smaller species of owls, such as northern pygmy owls (*Glaucidium gnoma*), by the interval between successive calls, approximately 1 min in the case of the larger owls and 30 s or less in the case of the smaller species. Calling bouts of large owls typically lasted less than 15 min, whereas the smaller owls called for longer periods. Bouts of calls were identified by eye. When the signal-to-noise ratio (SNR) exceeded background levels by more than 5 dB, bouts were marked for further analysis.

MSO and GHO calls could not be distinguished using time-history profiles. Based on GHO detection rates, it is unlikely that a substantial portion of the large owl events in the SLM data were the result of GHO calling in MSO activity centers. However, to

minimize the possible error in rates of call bouts GHO call bouts, analysis was limited to data from SLM sites within 400 m of an activity center. Sites were excluded if GHO were reported within 400 m of the instrument at any time during the season. As a check, bouts of calls collected by LD 824 instruments were examined using 1/3-octave band spectra as well. GHO could be distinguished in these data because their calls had substantially lower frequency than MSO calls.

Results

MSO Source Levels from Real-time Recordings

Real-time samples of calls were obtained from males in six territories (Table I). Typically, males could only be recorded from a single distance, so the spherical propagation model could not be fit to the data to estimate source level without additional assumptions.

A model was fitted to the data from all males combined (Figure 2). SL was estimated by fitting the maximum 125-ms segment in each call (L_{max}) to the spherical spreading model using a least-squares fit. The estimated SL for all males combined was 90 dB (N = 30, F = 1029.4, p < 0.001) but the proportion of variance explained by the model was somewhat low (R = 0.5805, R^2 = 0.3370). The 95% confidence limits ranged from 86 to 94 dB SPL.

In one case, the Hail Canyon territory, data from the resident male were collected at multiple distances, allowing an SL for the individual to be estimated. The fit of the spherical spreading model in the range from 10 to 80 m was excellent. SL was estimated at 94 dB (N = 5, F = 2464.959, p = 0.000001, R = 0.92, R^2 = 0.84). The 95% confidence limits ranged from 91 to 98 dB SPL.

Estimated Range of MSO Detections Based on Source Level Estimates

Based on the estimates of source levels of four note hoots, SLM stations could be expected to detect owl calls at substantial ranges. The distance at which MSO calls might be detected along an unobstructed line of sight was estimated using the spherical spreading model. Under conditions typical in the forest at night, with background noise at approximately 30 dB L_{Aeq} or lower, owls with an estimated SL of 86 dB could be detected at a range of 355 m or greater with an SNR of 5 dB or more. Those with call levels at the upper end of the range (94 dB SL), such as the Hail Canyon male, could be detected at ranges of 900 m or more.

However, at ranges in excess of approximately 400 m, topographic effects on propagation could be expected to predominate. Over 80% observer detections of owls during the years covered by the analysis were made at ranges of 400 m or less (Bowles unpub. data). Additional processing using a single-event propagation model would be required to estimate the effective range of reception at longer ranges (Bowles et al. 2002).

Estimated Rate of MSO Vocalizations Detected at Fixed Points

Over 335,000 hours of two-second time-interval data were collected during 2002 to 2005 from the array of SLMs. Typically, over 2000 hours were collected per sampling site per 105-day season. A total of 999 owl calling bouts were identified (Table II).

Owl events in the SLM data were produced by two sources, owls and humans imitating MSO calls during surveys. Calling bouts produced by human observers were identified by searching for marked events at SLM sites within 400 m of a survey call point and within ±15 min of the time the point was called. These events were uncommon in the SLM data because survey points were not called if they were within 400 m of a known activity center. Only 36 events likely to be produced by human callers were found in the four years of data examined (3 – 14 per year). These were eliminated from the dataset. The 958 remaining events were used to estimate rates and levels of calling bouts.

Calls were narrowed to the dataset thought to be produced by MSO by eliminating (1) bouts detected during the day, (2) bouts with short intervals and high bout counts, which were likely to be produced by small owls (7% of sample), (3) call bouts at sites where GHO had been detected within 400 m, and (3) SLM sites more than 400 m from an MSO activity center. A total of 860 call bouts collected from 148 SLM sites remained in the dataset after elimination.

Using this dataset, MSOl events occurred at a rate of 5.8 per season per SLM site. The number of individual calls per bout averaged 9.7 (95% CI 7.8 to 11.6 calls, range 1 - 60). Nearly all the calls were detected during periods when the background noise levels were close to the noise floor of the instruments (16 – 20 dB). The signal-to-noise ratio (SNR) above the instrument noise floor was typically close to the 5-10 dB criterion used during the bout identification process. Mean SNR above baseline of the maximum two-second sample in each bout was 12.6 dB (95% CI 11.2 to 14.0 dB, range 5 dB to 33 dB).

Conclusions

The results of this analysis indicate that MSO calls can be detected from fixed monitoring sites near owl activity centers. Estimated owl SLs were in the range from 86 to 94 dB. Based on preliminary projections using a simple propagation model (spherical spreading, line-of-sight transmission), these calls can be detected at ranges that would make automated survey stations practicable.

During the 2000 – 2005 study in the Gila National Forest, monitoring sites were chosen to minimize noise disturbance to owls during instrument servicing. Instruments were therefore placed several hundred meters from the center of owl activity centers. In this configuration, an estimated 5.8 MSO calls per year per site were detected in over 2000 hours of monitoring per site. To obtain these data, over 335,000 hours of time-history

data had to be processed. However, even with this extensive coverage, some activity centers known to be occupied by MSO based on acoustic lure surveys did not register any calling bouts at all. The low return per unit of monitoring effort suggests that monitoring stations must be designed for deployment in the activity center itself. Characteristics of an optimal sampling array are given in the next section.

The rate of MSO calling bouts estimated from the SLM data could have been somewhat inflated by calling bouts of GHO. However, data in areas where GHO had been detected were eliminated before analysis, making it unlikely that GHO calling bouts represented more than a few percent of the sample. GHO were never detected in close proximity to roosting and nesting areas by monitoring teams (Bowles unpub.), nor were small owls detected commonly (7% of the original sample). Because the rate of MSO calling bouts was probably an underestimate given the distance between SLMs and activity centers, the estimate of 5.8 bouts per site per season should probably be used as is.

MSO apparently chose roosting and nesting sites that were not occupied by other species or excluded other species after occupying an area. However, without real-time data to confirm the species of the caller, species could not be distinguished absolutely. This finding suggests that samples of real-time data should be collected during call bouts to enable the species of the caller to be identified unambiguously.

SNR of calls at SLM sites was typically low relative to the noise floor of the recording instruments (mean SNR of 13 dB, mean L_{Aeq2s} 32 dB). Figure 4 shows a series of idealized transmission loss curves for an owl call with an estimated SL of 90 dB. Detection ranges for varying levels of background noise are plotted presuming $1/r^2$ spreading loss. Curves for SNR of 0 dB to 30 dB are shown. Although real-world transmission loss is complicated by factors such as topography, atmospheric conditions, relative altitude of sources and receivers, and owl orientation, these idealized curves make the technical requirements of an acoustic survey clear. At low SNR (~10 dB) under quiet conditions, owls would be detectable along a line of sight for thousands of meters. During the study in the Gila National Forest, observers made detections out to approximately 2000 m under real-world conditions, although most detections were made at ranges less than 600 m. Acoustic lure survey protocols for the MSO, which are designed to collect an exhaustive inventory of MSO in an area, specify a distance of 800 m between successive calling points (USFWS 2003)

However, samples used to estimate source level, caller sex, and possibly individual identity must have higher SNR, on the order of 30 to 50 dB. Figure 4 shows that at under typical noise conditions, calls must be collected at ranges of approximately 50 to 100 m to obtain such data. The results of the real-time data collection effort support this conclusion. Therefore, detection and identification may best be regarded as different tasks requiring sampling at different spatial scales.

The results of the study also suggest that automated identification of owl events will be required. Bouts of owl calls were detected an average of approximately six times per season out of over 2000 hours of sampling per site. All of the data for collected from

2002 – 2005 were processed by eye (over 335,000 hours of SLM data were examined). Even with custom software designed to speed up the analysis, four to six staff members worked throughout each field season to keep up with this volume of data. Even so, the SLM array did not cover all the areas known to be occupied by owls - only 38 of approximately 83 areas could be monitored per season - so this effort would have to be doubled or more to detect owls in all the areas where they might have occurred in the Gila National Forest study site, a 485 km^2 area. Therefore, machine identification of call bouts will be essential to allow acoustic surveys to be conducted efficiently.

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Table I. Summary of Four-Note Hoots in Real-Time Recordings.

Territory	Sample of Four-Note Hoots with Distance Estimate
GILCS	2
HAIL	5
RK3	2
RK7	4
SCH2	2
SCHSNOW	6
Total	21

Table II. Summary of Owl Events Detected in SLM Data, 2002 to 2005.

Year	Count Owl Events	Nocturnal Events (1700-0800)	Nocturnal Events Matched to Call Points
2002	321	320	14
2003	126	125	3
2004	177	174	10
2005	375	375	9
Total	999	994	36

Table III. Owl Events Sampled to Determine Incidence of Mexican Spotted Owl Calls.

Year	Owl Events Sampled	Events Large Owls	Number Sites	Owl Events/ Site	Large Owl Events/Site
2002	100	94	38	2.63	2.47
2003	100	93	27	3.70	3.44
2004	100	88	32	3.12	2.75
2005	100	96	34	2.94	2.82
Total	400	371	131	3.05	2.83
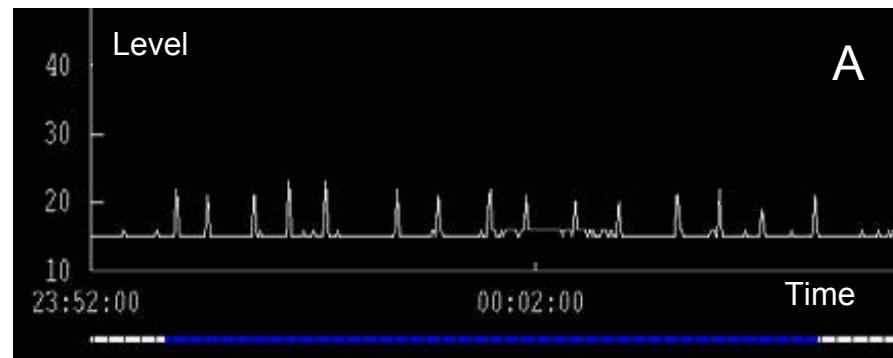
Figure 1. Time-history of a calling bout of a large owl (a) and small owl (b).

Model: Lmax = Constant - 20*log$_{10}$(Distance)

y = 84.3443 - 20*log$_{10}$(x)
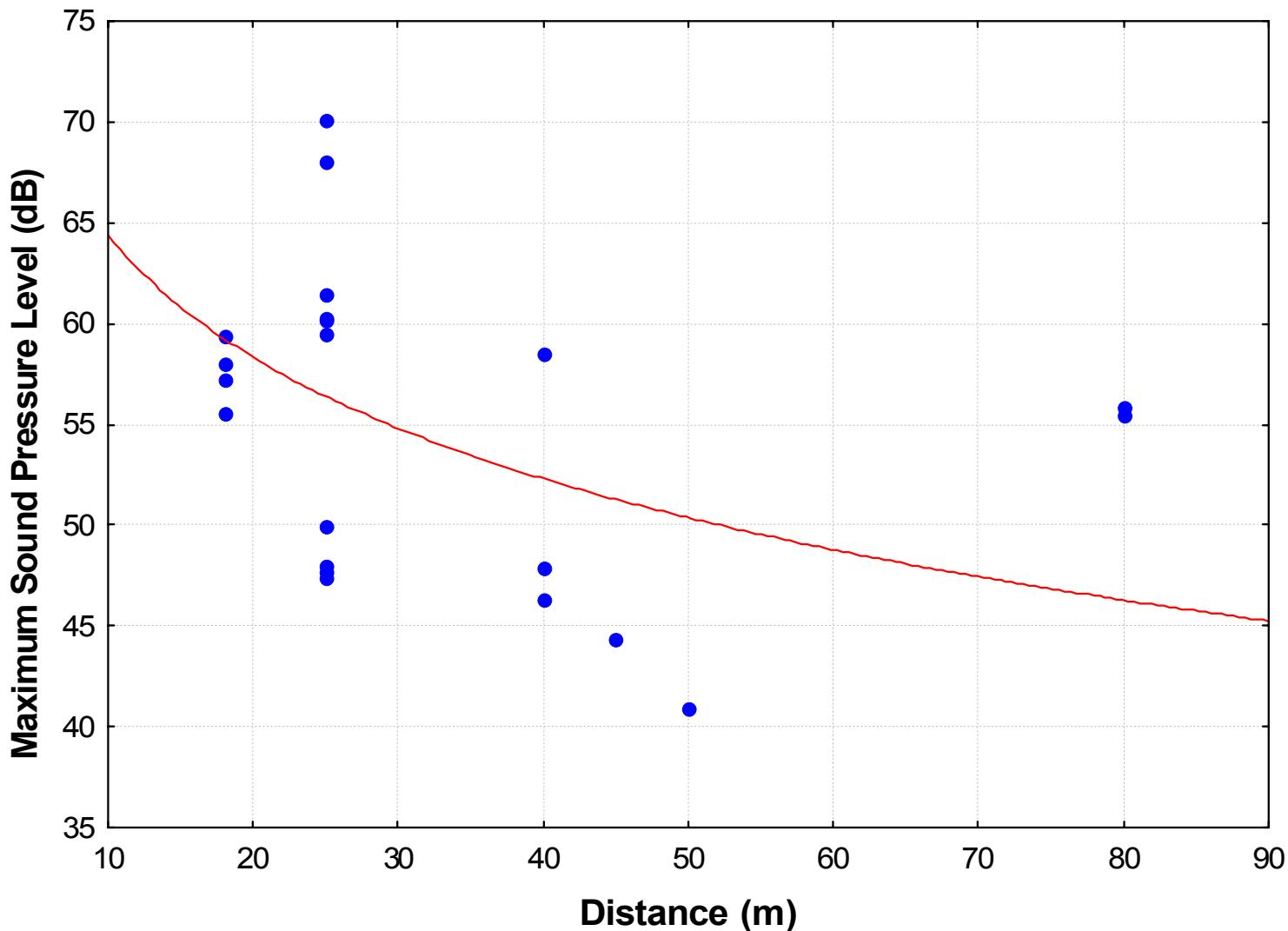
Figure 2. Fit of spherical spreading model to measured maximum sound pressure level of male four-note hoots.
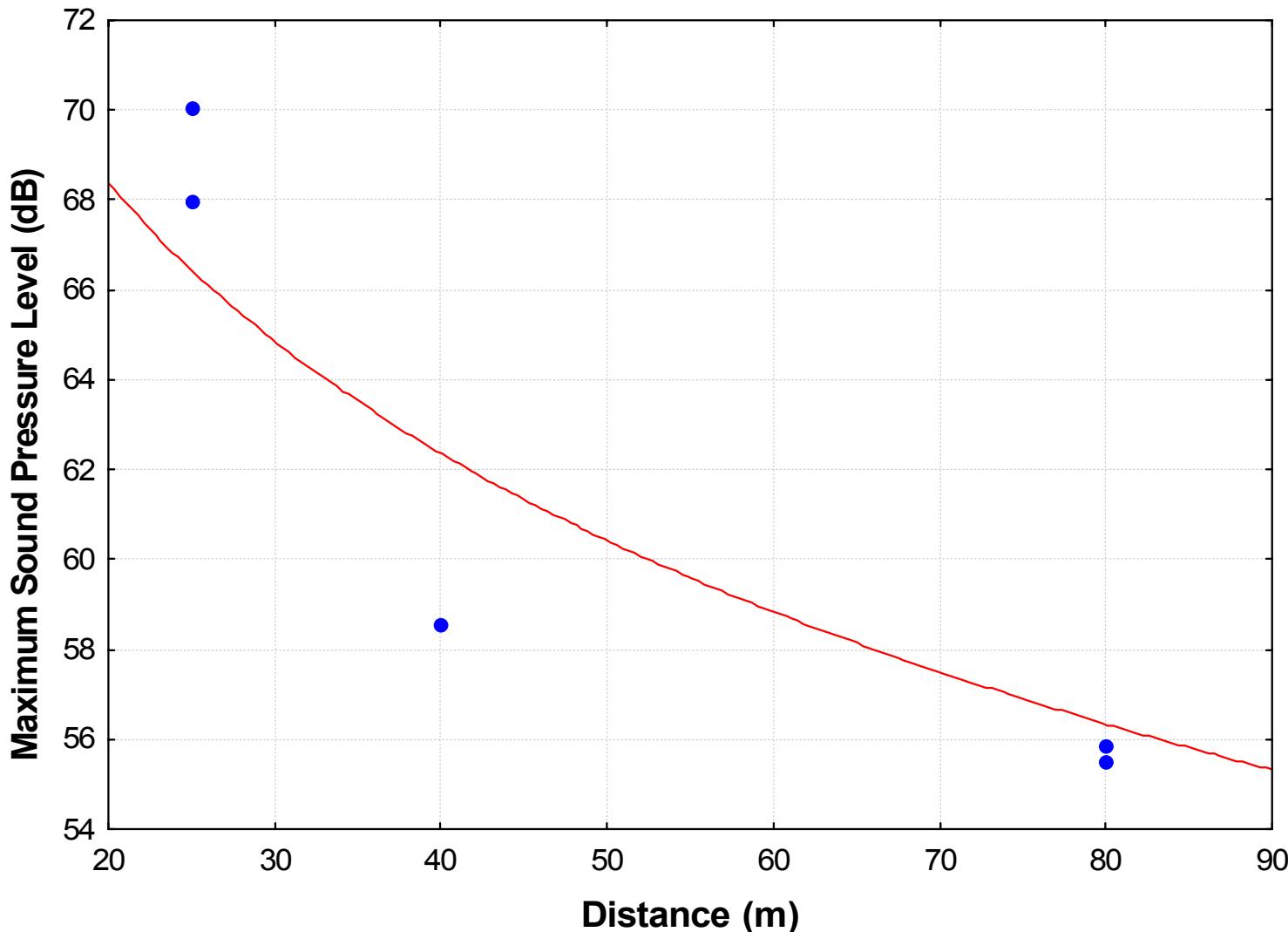
Figure 3. Fit of spherical spreading model to measured maximum sound pressure level of four-note hoots produced by the Hail Canyon male (all years combined).
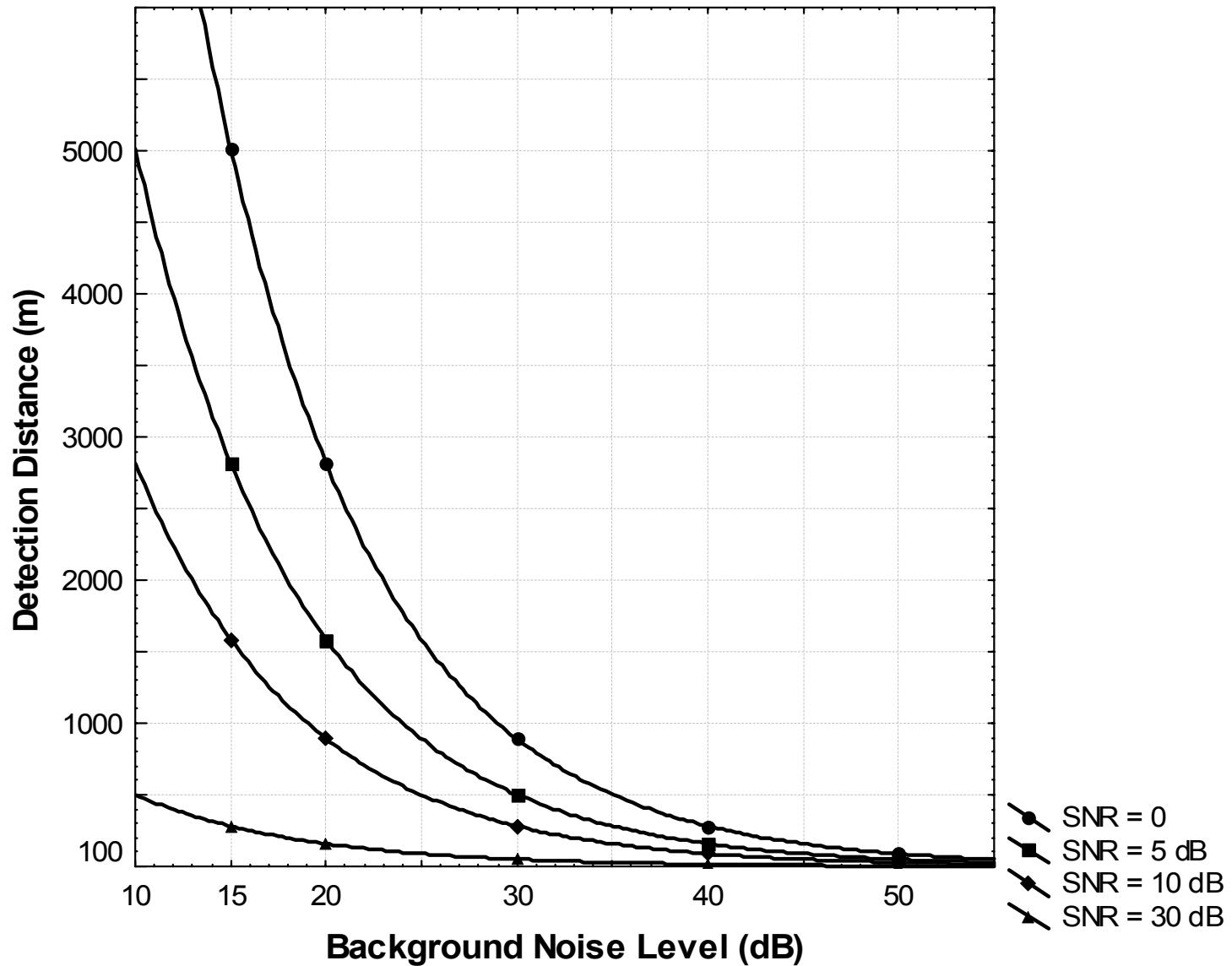
Figure 4. Idealized relationships between detection distance and background noise level for calls. Plot shows functions based on the estimated source level of male four-note hoots and detections at varying SNR.

Classification Key for Mexican Spotted Owl Vocalizations Using Nine Acoustic Measurements.
Results are from training data set.

Decision &Criteria	# of files, P(x) for classes (F, M, and O), and Classification	
1) Slope<142.26	226, 0, 0, 1	**Owlet**
1) Slope>142.26	545, 0.2697, 0.7303, 0	
2) MeanFo<707.95	433, 0.0924, 0.9076, 0	
3) MinFo<477.5	388, 0.0490, 0.9510, 0	
4) MeanFo<573.2	334, 0.0269, 0.9731, 0	
5) MinHNR<-225.815	189, 0, 1, 0	**Male**
5) MinHNR>-225.815	145, 0.0621, 0.9379, 0	
6) MinPos<0.984	129, 0.0310, 0.9690, 0	
7) MaxHNR<22.59	38, 0.1053, 0.8947, 0	
8) MeanFo<509.5	25, 0, 1, 0	**Male**
8) MeanFo>509.5	13, 0.3077, 0.6923, 0	
9) PeakPos<0.3295	6, 0, 1, 0	**Male**
9) PeakPos>0.3295	7, 0.5714, 0.4286, 0	**Female**
7) MaxHNR>22.59	91, 0, 1, 0	**Male**
6) MinPos>0.984	16, 0.3125, 0.6875, 0	
10) MinPos<0.9875	5, 1, 0, 0	**Female**
10) MinPos>0.9875	11, 0, 1, 0	**Male**
4) MeanFo>573.2	54, 0.1852, 0.8148, 0	
11) Jitter<0.00932433	39, 0.0769, 0.9231, 0	
12) MaxHNR<23.72	5, 0.4000, 0.6000, 0	**Male***
12) MaxHNR>23.72	34, 0.0294, 0.9706, 0	**Male***
11) Jitter>0.00932433	15, 0.4667, 0.5333, 0	
13) MinPos<0.8215	10, 0.3000, 0.7000, 0	**Male**
13) MinPos>0.8215	5, 0.8000, 0.2000, 0	**Female**
3) MinFo>477.5	45, 0.4667, 0.5333, 0	
14) Jitter<0.00966708	33, 0.30300, 0.69700, 0	
15) PeakPos<0.265	11, 0, 1, 0	**Male**
15) PeakPos>0.265	22, 0.4545, 0.5455, 0	
16) MinHNR<-1.095	16, 0.62500, 0.3750 0	
17) StdevHNR<5.67642	9, 0.8889, 0.1111, 0	**Female**
17) StdevHNR>5.67642	7, 0.2857, 0.7143, 0	**Male**
16) MinHNR>-1.095	6, 0, 1, 0	**Male**
14) Jitter>0.00966708	12, 0.91670, 0.08333 0	**Female**
2) MeanFo>707.95	112, 0.9554, 0.0446, 0	
18) MeanFo<736.25	18, 0.7222, 0.2778, 0	
19) Slope<3704.7	5, 0.2000, 0.8000, 0	**Male**
19) Slope>3704.7	13, 0.9231, 0.0769, 0	**Female**
18) MeanFo>736.25	94, 1, 0, 0	**Female**

* These classifications serve no useful purpose in this tree, since both are classified as male. In practice, the split to create these classes would be pruned from the tree.